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On the Structural Geology of the Southern Province between Sault Ste. Marie and Espanola, Ontario

2001

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Open File Report 5995

On the Structural Geology of the Southern Province between Sault Ste. Marie and Espanola, Ontario

by

S.L. Jackson

2001

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Abstract

Paleoproterozoic Huronian Supergroup rocks of the Southern Province are well known for their contained uranium ores at Elliot Lake, nickel-copper ores and impact-related features at Sudbury, and thick formations of sedimentary strata. To improve the understanding of the structural geology of the western Huronian Supergroup, the Aberdeen, Flack Lake and May Township areas were studied between 1992 and 1994. Structural analysis of these areas is presented within this report.

Southern Province rocks exhibit a beguilingly simple concave to the north structural grain. Regional structures are commonly attributed to compression during Penokean orogeny; however, structural, intrusive and metamorphic relationships permit other interpretations. North of the Murray Fault, rocks of low metamorphic grade are deformed about generally upright folds and reverse and/or thrust faults. The folds affect Nipissing gabbro bodies (intruded at 2.22 Ga) and the Sudbury Igneous Complex (1.85 Ga) and are commonly associated with weakly to moderately developed, steeply dipping, axial planar cleavage. South of the Murray Fault, there is evidence for at least 3 deformational events including 1) pre-Nipissing gabbro faulting and large-scale folding related to syn-depositional and/or post-depositional deformation of unconsolidated strata; 2) "D_1" layer-parallel structural elements reflecting high extensional strain that formed pre- to syn-peak metamorphism; and 3) "D_2" regional folds and faults that parallel structures north of the Murray Fault, which deform metamorphic isograds, and are associated with a crenulation cleavage. Both D_1 and D_2 structures south of the Murray Fault affect the Nipissing gabbro. Furthermore, some field observations may indicate that D_2 structures postdate the Cutler Batholith (1.75 Ga).

The origin of medium-grade metamorphic assemblages, involving staurolite and biotite in the McKim Formation south of the Murray Fault, is a perplexing aspect of Southern Province tectonics. This metamorphism was previously attributed to crustal thickening during the Penokean orogeny. Although this could explain the mesoscopic D_1 structural elements oriented at a low angle to bedding, the lack of regional structural evidence for the required thickening during D_1 and the conclusion that metamorphism predates regional folding do not support such an interpretation. Furthermore, geobarometry indicates relatively low-pressure (2 to 3 kilobars; 6 to 10 km) metamorphism at a crustal thickness close to, or less than, the estimated thickness of the Huronian clastic prism, which would also seem to preclude metamorphism related to crustal thickening. Crustal extension and increased mantle heat flow might better explain the near layer-parallel foliation, lack of structural evidence for significant crustal thickening, and the low-pressure metamorphism. Roscoe and Card recently postulated that post-sedimentation breakup of the Superior craton may have occurred as late as 2.1 Ga rather than shortly after 2.45 Ga. Post-metamorphic regional compression, resulting in generation of the large-scale regional folds that characterize the Southern Province, may have occurred circa 1.75 Ga. The above interpretation invokes substantial pre- and post-Penokean Orogen tectonic events, but does not require deformation or metamorphic events in the 1.85 to 1.82 Ga interval.

On the Structural Geology of the Southern Province between Sault Ste. Marie and Espanola, Ontario

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Manuscript reviewed and revised by R.M. Easton and M. Easton.

Introduction

Paleoproterozoic rocks of the Huronian Supergroup, Southern Province (Figure 1) are well known for their contained uranium ores at Elliot Lake (e.g., Roscoe 1969), nickel-copper ores and impact-related features at Sudbury (e.g., Dietz 1964; also papers *in* Pye et al. 1984), and the thick accumulations of sedimentary rocks, which include glaciogenic diamictites deposited during cyclic sedimentation (e.g., Young 1991, 1995). The sedimentary succession was deposited following emplacement of west-northwest-striking diabase dikes at roughly 2.45 Ga (Heaman 1997) and gabbro–anorthosite intrusions and rift-related volcanic rocks of similar age (Krogh et al. 1984). Southerly directed paleocurrents, southerly thickening of the Huronian clastic wedge, and the presence of glaciogenic units have led many workers to favour a south-facing, glacially influenced, passive margin depositional environment for the Huronian Supergroup (e.g., Miall 1985; Bennett et al. 1991; Young 1991). Roscoe and Card (1992, 1993), however, suggested that Huronian Supergroup rocks were deposited in a broad, southward-deepening, intra-continental trough that was elongate in the direction of the Matachewan dikes. In their model, passive margin development postdates deposition of the Huronian Supergroup and resulted from westward and clockwise drift of the Wyoming craton relative to the Superior craton at roughly 2.1 Ga.

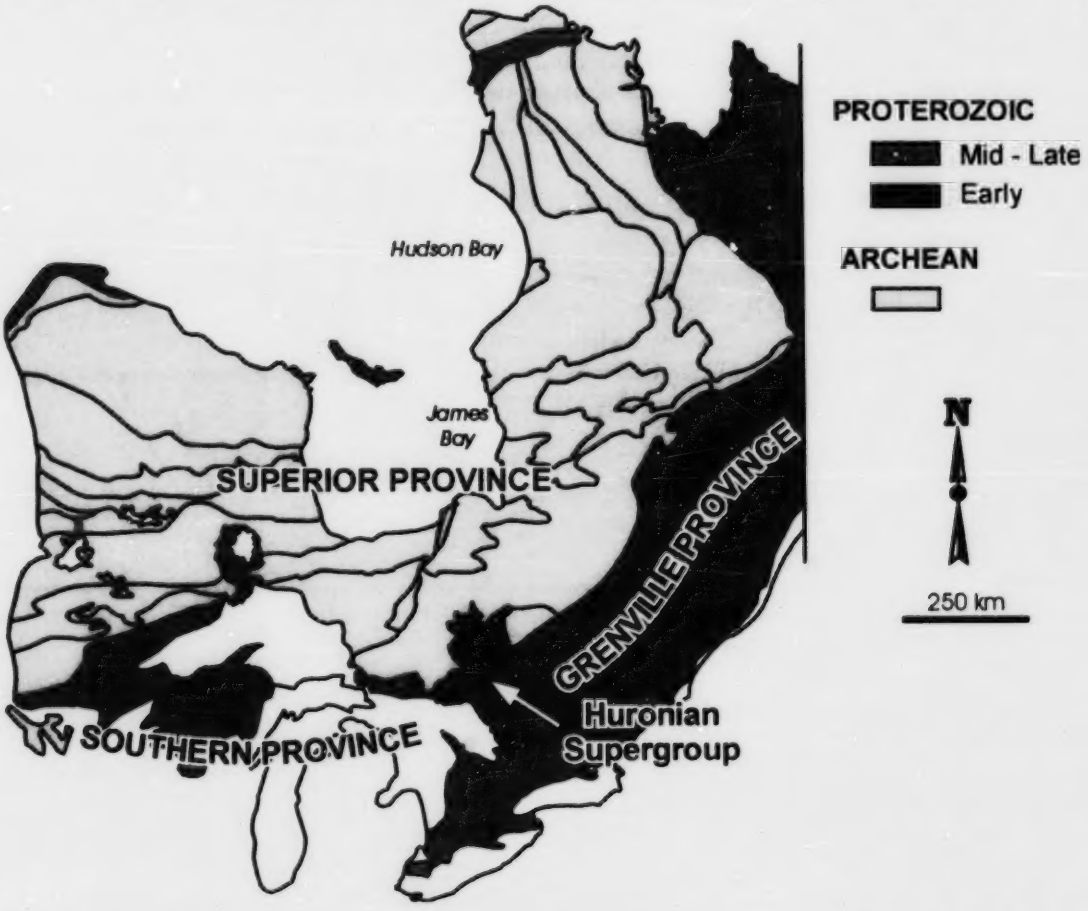

Figure 1. Location of the Paleoproterozoic Huronian Supergroup on the southern margin of the Archean Superior Province.

Several deformational episodes affected the Huronian Suprergroup strata (Card et al. 1972). A syndepositional event produced some relatively large-scale folds and faults that predate emplacement of Nipissing gabbro circa 2.2 Ga (Young 1983; Young and Nesbitt 1985). Post-depositional deformation resulted in large-scale folds and faults (Figure 2), such as the Quirke Lake Syncline, Chiblow Anticline, Murray Fault, and Flack Lake Fault, which typify the structural style of the Southern Province and at least in part, if not wholly, postdate the Nipissing gabbro and the Sudbury Igneous Complex (ca. 1.85 Ga). These structures have commonly been attributed to Penokean orogeny circa 1.85 to 1.82 Ga (Van Schmus 1980). In the area of the Grenville Front, there are significant magmatic and tectonic events at circa 1.7 Ga, 1.5 Ga and circa 1.0 Ga (Krogh 1994; Davidson and van Breemen 1994).

Most structural studies related to the Huronian Supergroup have concentrated on the Sudbury Structure–Grenville Front area (Brocum and Dalziel 1974; Dalziel et al. 1969; Shanks and Schwerdtner 1991; Milkereit et al. 1992; Henderson 1972; Davidson 1992). West of the Sudbury Structure–Grenville Front area, Card (1963), Blackburn (1967) and Church (1968) have reported on regional to meso-scale structures including the identification of multiple deformation events, particularly in rocks south of the Murray Fault. Zolnai et al. (1984) presented regional structure sections of the Elliot Lake–Sudbury area.

To improve the understanding of the structural geology of the western Huronian Supergroup, 3 regions were studied between 1992 and 1994 (*see* Figure 2 for locations): the Aberdeen area (Jackson 1994a); the Flack Lake area; and the May Township area (Jackson and Henderson 1993; Jackson et al. 1993). The purpose of this report is to summarize the structural geology of these 3 regions, identify some implications for mineral deposits, and provide a revised deformation history of the Southern Province.

Figure 2. Distribution of Huronian Supergroup rocks in the Sault Ste. Marie–Elliot Lake area and locations of regions examined in this study (Sault Ste. Marie is located just west of the western boundary of figure). The Murray Fault is shown to extend into the North Channel of Lake Huron rather than to the northwest into the Aberdeen area (see text).

Regional Geology

Recent summaries of the Southern Province with an emphasis on the Huronian Supergroup include those of Card et al. (1972), Bennett et al. (1991) and Roscoe and Card (1992). These reviews offer a more comprehensive treatment than the brief synopsis presented below.

The Huronian Supergroup is a stratigraphic succession 5 to 10 km thick that lies unconformably on top of Archean basement. Stratigraphy of the succession (Figure 3) is well established through numerous township-scale and 1:50 000-scale maps, and detailed stratigraphic studies (*see* references *in* Bennett et al. 1991). The supergroup consists of 4 lithostratigraphic groups, each with a basal unconformity when proximal to Archean basement at the basin margin. Basal contacts exhibit conformable–disconformable relationships in more distal, that is, more southerly, regions. The lowermost Elliot Lake Group includes bimodal, rift-related volcanic rocks (Jolly 1987) and uraniferous quartz-pebble conglomerate (Roscoe 1969), quartz-arenitic to subarkosic sandstone, and fine-grained wacke to mudstone. Gabbroic anorthosite bodies intrude Archean basement and are commonly considered to be intrusive equivalents of

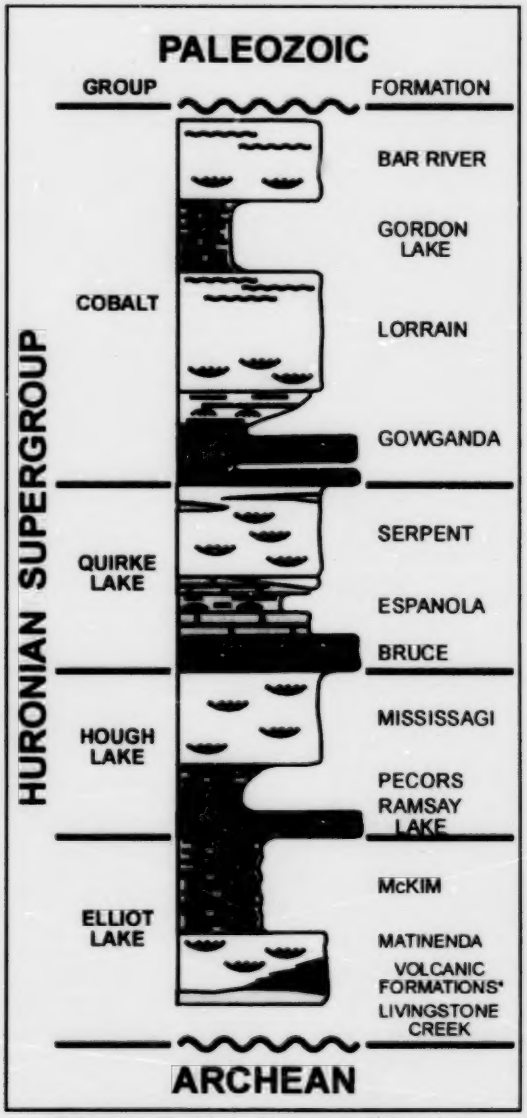

Figure 3. Stratigraphic column of the Huronian Supergroup.

volcanic rocks in the Elliot Lake Group. Several reports (e.g., Dressler 1984; Bennett 1978), however, provide evidence for an erosional unconformity between the gabbro-anorthosite bodies and units stratigraphically *below* the Huronian volcanic rocks. Basal units of the Hough Lake, Quirke Lake, and Cobalt groups include matrix-supported conglomerates commonly referred to as diamictites. The remainder of each of these 3 groups consists of thick formations of subarkose to quartz arenite, and formations of fine-grained wacke-siltstone or carbonate-rich sedimentary rocks. These groups, and the formations within them, are arranged in a repeating, or cyclical, fashion (e.g., Roscoe 1969). Stratigraphy of the Huronian Supergroup is summarized in Figure 3 and is based on Roscoe (1969), Card et al. (1972), Frarey and Roscoe (1970), Wood (1973), Young (1991) and Bennett et al. (1991, and references therein).

Significant changes in stratigraphic thickness occur across some regional faults, for example, the Flack Lake and Murray faults (e.g., Bennett et al. 1991, and references therein). North of the Flack Lake Fault, the Gowganda Formation is a thin veneer resting on Archean basement; however, south of the fault, the formation is more than 1000 m thick. Similarly, the McKim Formation, north of the Murray Fault, is tens of metres thick, whereas south of the fault, it is probably in excess of 1000 m thick. The thickness and facies variations across the Flack Lake and Murray faults suggest that the faults were down-to-the-south syn-sedimentary growth faults that were reactivated during compression related to the Penokean orogeny (e.g., Zolnai et al. 1984).

The Murray Fault, in addition to marking stratigraphic thickness variations, also marks profound changes in structural style, metamorphic grade and magmatic associations (Card et al. 1972). Deformation is more complicated and of greater intensity south of the fault than to the north. Likewise, metamorphic grade is higher immediately south of the fault (amphibolite facies transitional southward to greenschist facies) than to the north (greenschist to subgreenschist facies). South of the fault, there are several 1.75 Ga (Davidson and van Breemen 1994) and younger granitoid complexes (e.g., Cutler batholith), whereas, north of the fault, there are no such intrusions.

Intruding the Huronian Supergroup (Figure 4) are granites near Sudbury (2.48 Ga: Krogh et al. 1996); Nipissing gabbro sills (2.22 Ga: Corfu and Andrews 1986); the Eden Lake pluton (1.75 Ga:

Figure 4. Distribution of rocks that are intrusive into the Huronian Supergroup.

Sullivan and Davidson 1993); the Sudbury Igneous Complex (1.85 Ga: Krogh et al. 1984); granitoids, including the Cutler batholith, and granitoids near Killarney (1.75 to 1.70 Ga: van Breemen and Davidson 1988; Davidson et al. 1992; Davidson and van Breemen 1994); granitoids and dikes near the Grenville Front (1.45 Ga: Krogh 1994); and diabase dikes (1.25 Ga: Dudas et al. 1994).

Open to tight, upright to inclined folds (e.g., Chiblow Anticline, Sudbury Basin) and steeply to moderately south-dipping, north-verging, reverse faults (e.g., Murray Fault, Flack Lake Fault) are characteristic of the structural style of the Southern Province (Card et al. 1972; Zolnai et al. 1984). Zolnai et al. (1984) characterize the regional structure of the Huronian Supergroup as a thick-skinned, basement-involved, fold-thrust belt where the major thrusts are reactivated, listric, growth faults. Regional structures are commonly attributed to the Penokean orogeny, although, there is some debate regarding the expression of the Penokean orogeny in the Huronian Supergroup (Davidson et al. 1992; Card 1992); a point which will be returned to at the end of this report.

Aberdeen Area

STRATIGRAPHIC RELATIONSHIPS

This section on stratigraphic relationships is largely summarized from the maps of Frarey (1977). Mapping by Frarey (1977) in the western Huronian Supergroup, referred to here as the Aberdeen area, established regional variation in the distribution of Huronian formations. North of the McMahon Lake faults, metavolcanic rocks of the Elliot Lake Group are absent and strata of the Hough Lake, Quirke Lake and Cobalt groups all rest on Archean basement (Figure 5). Elliot Lake Group metavolcanic rocks are, however, exposed both south of the McMahon Lake faults and in the core of the Thessalon anticline (Figure 5). Another variation in unit distribution involves the Gowganda Formation. North of the McMahon Lake faults, Gowganda Formation rocks rest directly on Archean basement or Lower Huronian strata, or both. South of the McMahon Lake faults, the Gowganda Formation lies on top of Quirke Lake Group strata (note that the Serpent Formation may be absent in this area (Long 1976; Jackson 1994a)).

Consideration of the distribution of Huronian strata in the Aberdeen area and of contact relationships throughout the Sault Ste. Marie–Elliot Lake area indicate that 1) the base of each group represents a disconformity to unconformity near the current erosion trace of the Archean–Proterozoic boundary, that is, near the basin margin; and 2) south of the Murray Fault, in distal regions of the basin, the groups appear to be conformable to disconformable (e.g., Young 1991).

STRUCTURAL GEOLOGY

Fabric Relationships

Cleavage in fine-grained units of the Gordon Lake and Gowganda formations and both mica foliation and spaced cleavage in chloritic rocks of the Thessalon Formation (*see* Jackson 1994a) are generally west-northwest striking and steeply dipping (Figure 6). In the field, tectonic foliation in coarser units, such as the Lorrain Formation, are difficult to discern. Bedding-cleavage intersections are also west-northwest trending and are subhorizontal to gently plunging (Jackson 1994a). The bedding-cleavage intersections are parallel to the pole to the great circle encompassing the poles to bedding (Figure 6). This is consistent with the cleavage being an axial planar fabric formed during regional folding.

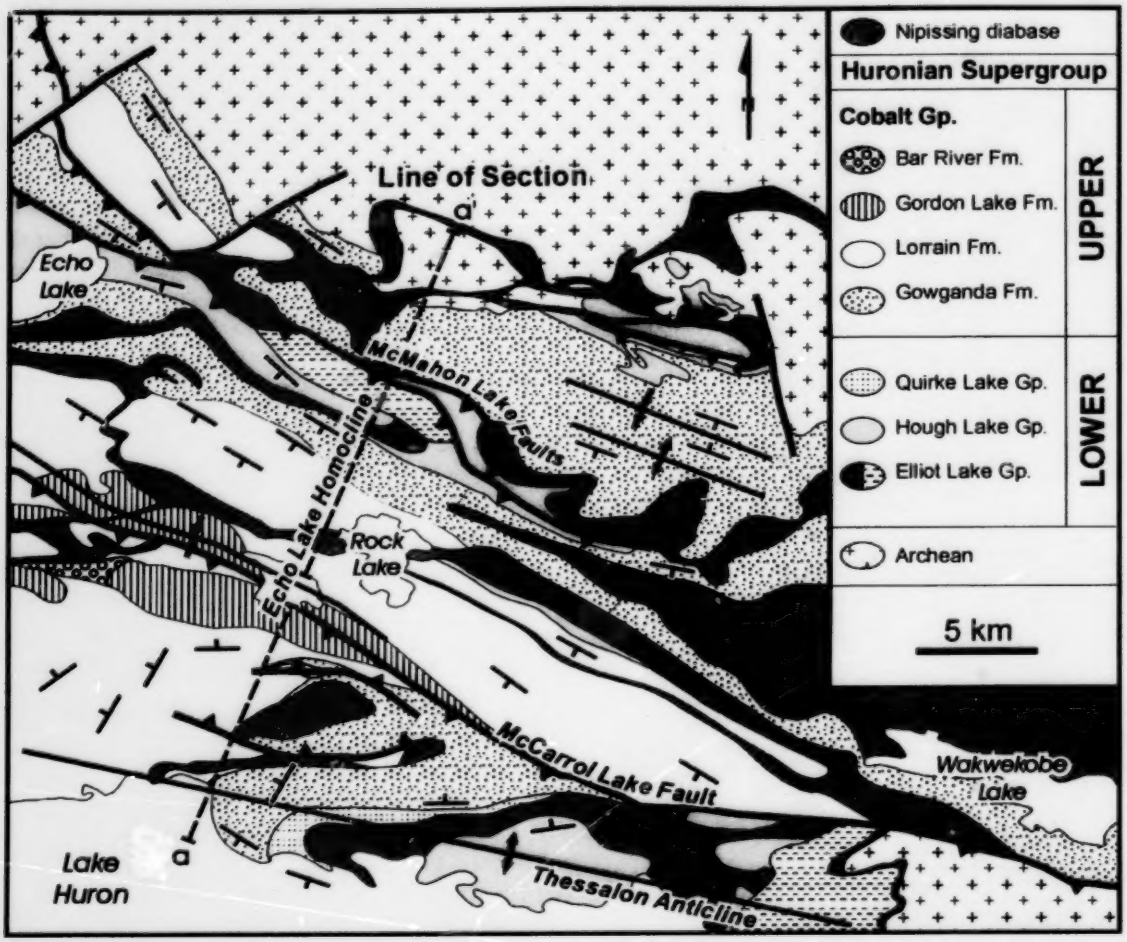

Figure 5. Simplified geology of the western Huronian Supergroup and location of section a–a' (Figure 8). Figure generalized *from* Frarey (1977).

Regional Structure

The Aberdeen area, mapped by Frarey (1977) and Jackson (1994a), is characterized by west-northwest striking structures (Figures 5, 7). Although numerous folds and faults dissect the area, the principal large-scale structures include the McMahon Lake faults, the Echo Lake homocline, the McCarrol Lake fault previously called the Murray fault in the map area; see below); and the Thessalon anticline. The name "McCarrol Lake fault" in this report is applied to both the McCarrol Lake fault identified by Frarey (1977) and that segment of the "Murray fault" extending southeastward from the eastern termination of Frarey's (1977) McCarrol Lake fault. Justification for this change is that in the Espanola–Sudbury region, complexly deformed amphibolite facies rocks in the hanging wall south of the Murray fault are juxtaposed against low-grade, less complexly deformed footwall rocks to the north (e.g., Card 1978b). Furthermore, in the Espanola–Sudbury region, the McKim Formation is dramatically thicker south of the fault than to the north. Such contrasts in metamorphic grade, structural style, and stratigraphy are not observed in the Aberdeen area. Nevertheless, the McCarrol Lake fault as defined in this study does have substantial stratigraphic separation (e.g., maps of Frarey 1977; Figure 5).

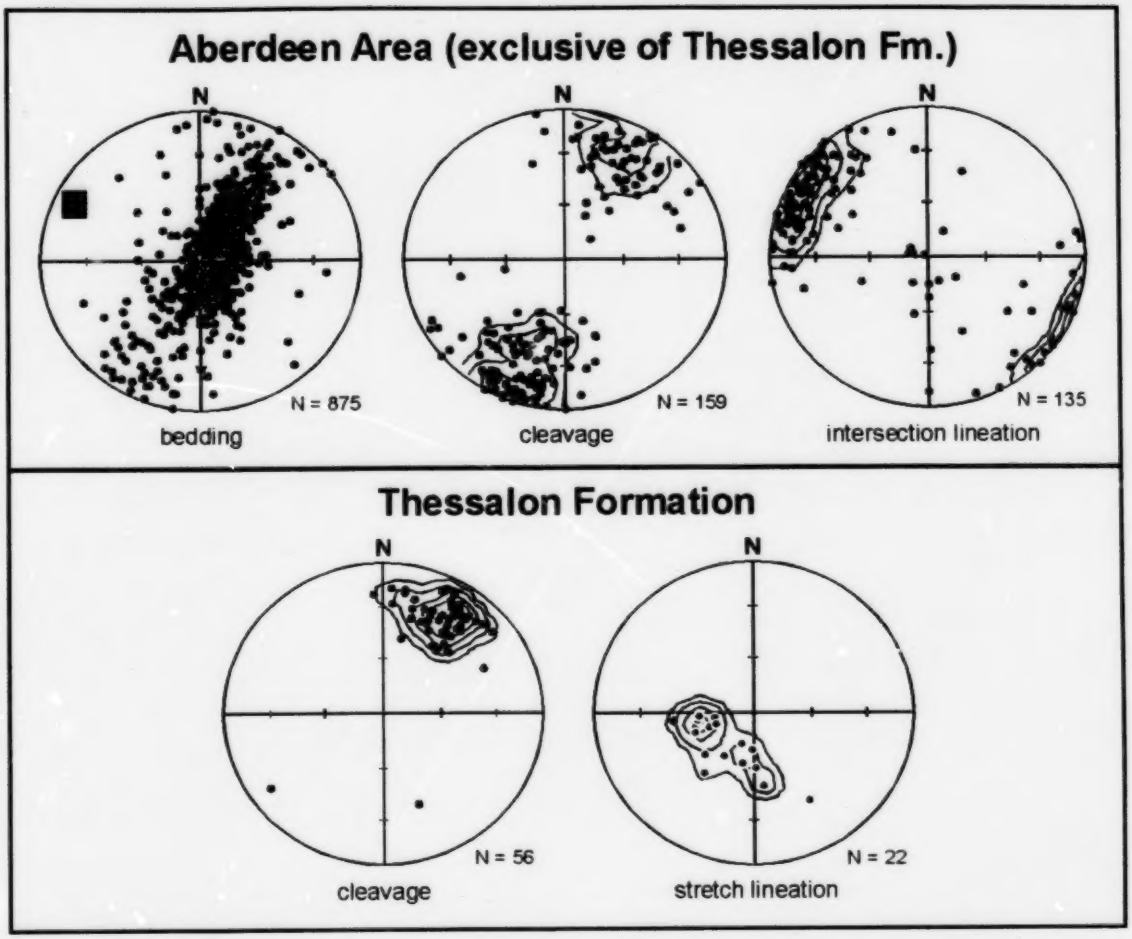

Figure 6. Structural elements of the Aberdeen area. Contours succesively increase in the order 1, 2, 5, 10, 15, and 20% per 1% area. Box in bedding stereonet indicates best fit pole to great circle of bedding plane poles.

Schematic structure sections (Figure 8) summarize the principal structural features of the Aberdeen area. Construction of the sections assumed the following conditions: an initial 25° southward dip to the basement–cover interface; that the McMahon Lake faults are south dipping and parallel to strata in the inferred hanging wall; and that the McCarrol Lake fault is steeply south dipping. A notable feature of the Echo Lake homocline is that units generally dip ~20° south in the southern part of the homocline and ~40° south in the northern part. The McMahon Lake faults juxtapose Lower Huronian strata of the Elliot Lake and Hough Lake groups. The strata are south dipping and south facing with older Elliot Lake Group strata structurally above younger Hough Lake Group strata. On this basis, the faults are considered south-dipping reverse faults. Stratigraphic separations illustrated in the section are consistent with those observed on Frarey's (1977) maps. Numerous minor faults and folds are not shown on the section (e.g., Figure 5). Although the sections are consistent with surface geology, there is considerable latitude in the completion of the deeper parts of the sections. As drawn, section B (Figure 8b) implies considerable horizontal displacement at, or near, the basement–cover interface and provides a possible alternative to the "inverted-growth-fault" expianation of structural–stratigraphic relationships (see below). Section C (Figure 8c), on the other hand, would be consistent with an inverted growth-fault model.

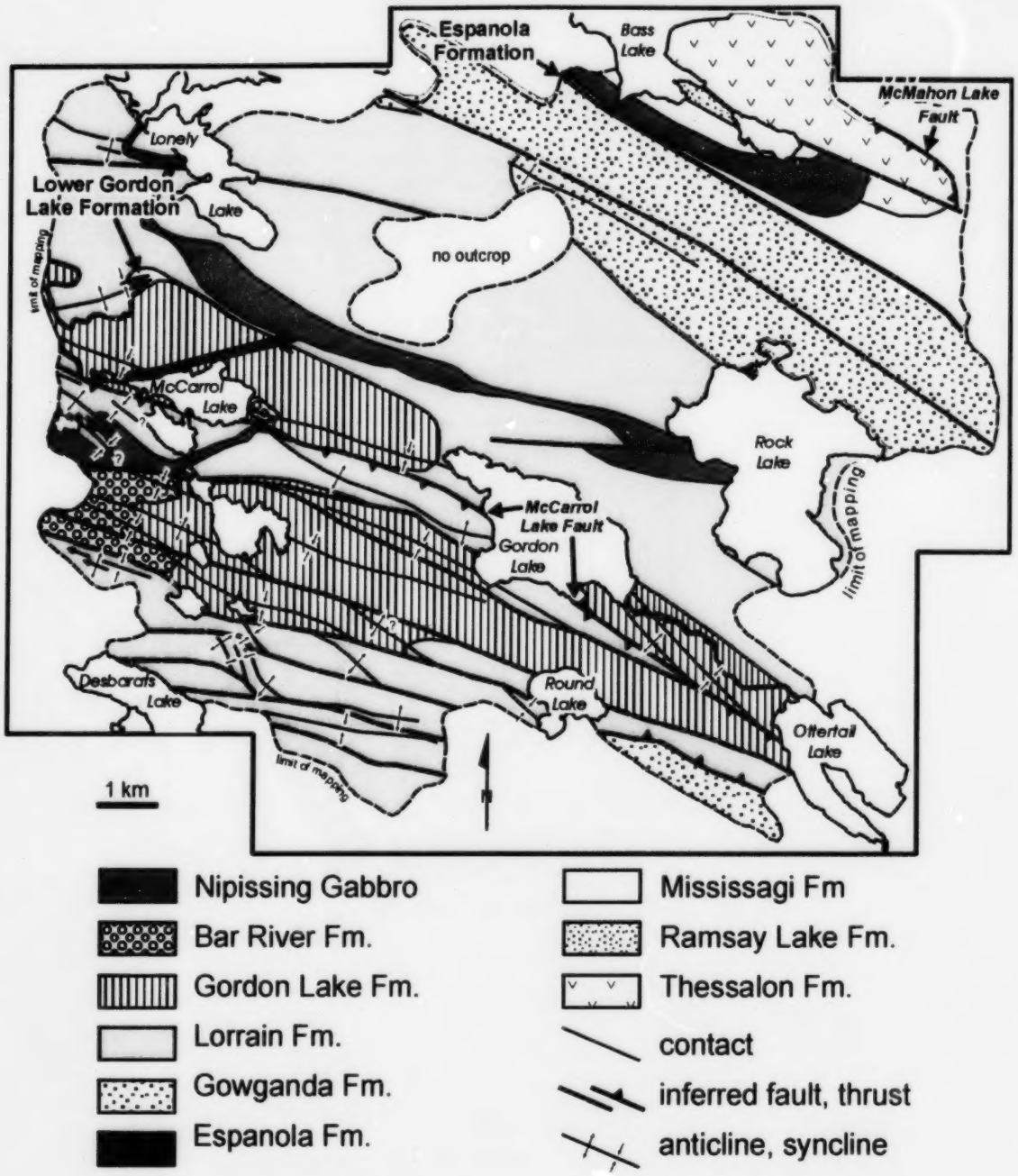

Figure 7. Generalized geology of the Aberdeen area (*after* Frarey 1977 and Jackson 1994). Note the general west-northwest strike to folds and faults and the slight clockwise orientation of fold axes with respect to faults in the southern part of map area. See Figure 6 for summary of structural elements.

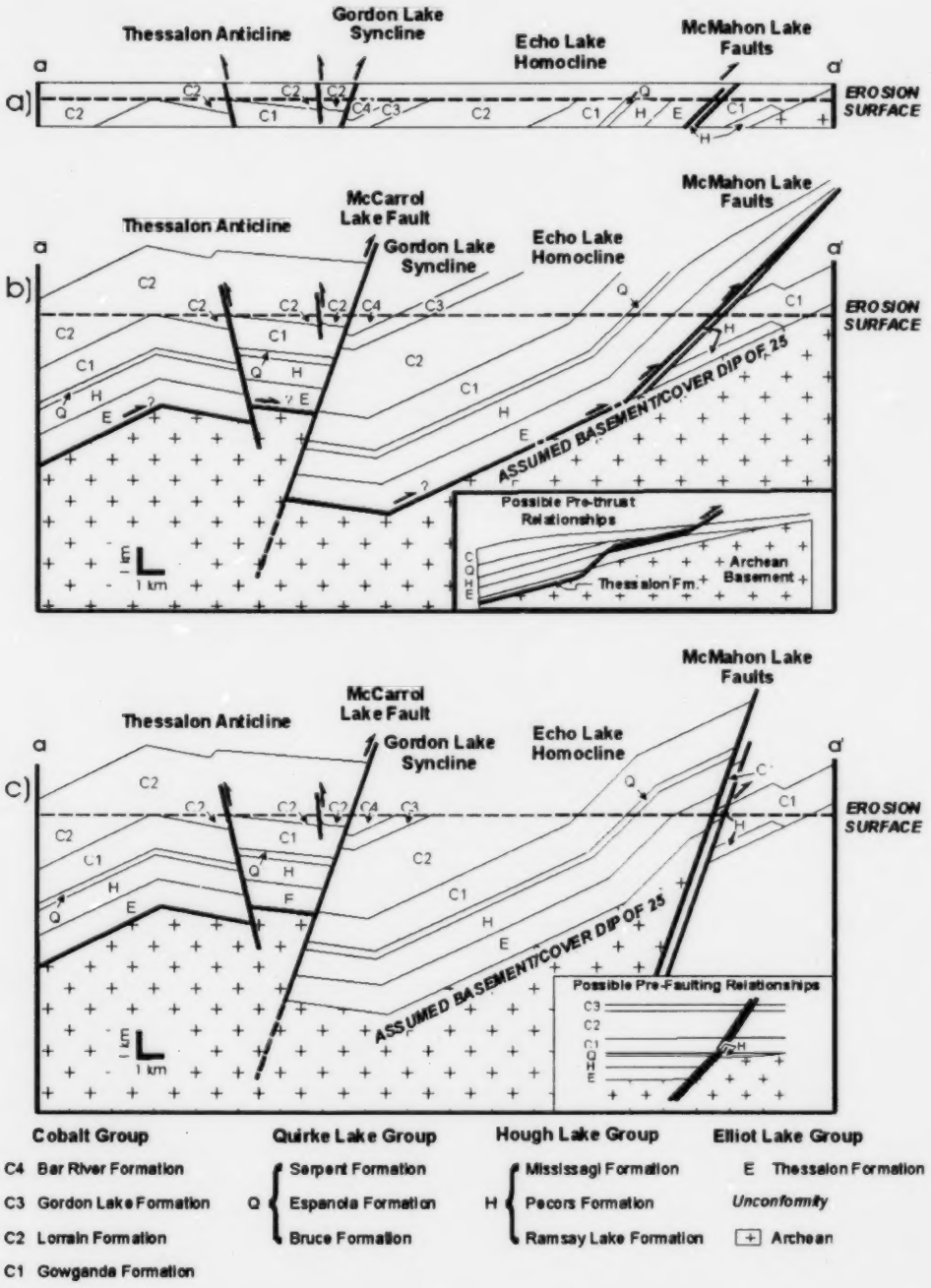

Figure 8. a) Schematic section through the western Huronian Supergroup. See Figure 5 for location of section. North of reverse faults shown near "a'", the Elliot Lake Group is not present at surface. Relationships at depth are speculative, consequently two alternative models are shown in (b) and (c). b) This section shows a model with considerable displacement at the basement-cover interface. Note that a detachment between the basement and cover is inferred, but not required, to account for surface geology. c) This section shows an inverted growth-fault model. The inset at lower right of the section in (c) schematically portrays possible pre-faulting relationships between the Hough Lake and Elliot Lake groups. Note that elsewhere there is evidence for an erosional unconformity between the Elliot Lake Group and lower Hough Lake Group (e.g., Figure 10).

The restriction of stratigraphically lower formations to the south side of a major fault in the Southern Province is commonly accounted for by assuming that the fault is an inverted growth fault (e.g., Zolnai et al. 1984). This model maintains that, during deposition, the southern hanging wall to the fault is down-dropped relative to the northern footwall. The result is thicker accumulations to the south and either thinner or non-accumulation to the north. The fault is "inverted" during compression wherein the south side is uplifted relative to the north side thereby juxtaposing thick accumulations of stratigraphically lower formations (possibly present only in the hanging wall of the fault) against stratigraphically higher formations in the footwall to the north of the fault. This is certainly an attractive explanation and appears reasonable for some areas; however, other scenarios can equally well account for the distribution of units and are consistent with the known geology of the Aberdeen area and the structure sections presented in Figure 8. Consider the relationship of progressively northward onlapping units depicted in the inset to Figure 8b. Several aspects of the prefaulting geometry are important. Firstly, Thessalon Formation volcanic rocks lie on Archean basement. Secondly, Thessalon Formation units are, in turn, unconformably overlain by Elliot Lake strata that onlap Archean basement to the north. Thirdly, proximal to the basin margin, these groups are unconformably overlain by northward onlapping Cobalt Group strata. Finally, distal to the basin margin, that is south of the Murray fault, the Quirke Lake Group is conformably overlain by Cobalt Group strata. Compressional deformation of this configuration of units could result in formation of thrust faults with flats following formation, group, or basement–cover boundaries and steeper, south-dipping ramps that cut up the stratigraphic section to the north. Such a scenario could result in the juxtaposition of Thessalon Formation units against stratigraphically higher groups that rest directly on Archean basement, *without* the requirement of the fault having been active during deposition.

At present, there are insufficient data to reject either the inverted-fault or thrust-fault-only scenario for the region south of the McMahon Lake faults; however, the latter scenario could explain the change in magnitude of dip observed in the Echo Lake homocline. The shallower dips would occur above the thrust flat and the steeper dips above a thrust ramp (Figure 8). If the pre-faulting geometry was comparable to that depicted in Figure 8b, then the structure section illustrated in Figure 8b would imply tens of kilometres of displacement along the basement–cover interface south of the McMahon Lake faults.

Flack Lake Area

STRATIGRAPHIC RELATIONSHIPS

This section on stratigraphic relationships is largely summarized from existing Ontario Geological Survey maps (Robertson 1961, 1962, 1963, 1968, 1969; Wood 1975; Siemiatkowska 1978; Siemiatkowska et al. 1981). In the Flack Lake area (Figures 2, 9), the Flack Lake fault separates two structural–stratigraphic domains: the Flack Lake homocline to the north and the Quirke Lake Syncline to the south. The Flack Lake homocline consists entirely of Cobalt Group strata and Nipissing gabbro; no Lower Huronian Supergroup strata are present north of the fault. South of the Flack Lake fault, strata of the Lower Huronian Supergroup, including Dollyberry Formation metavolcanic rocks, are present. In the homocline, the Gowganda Formation is a thin veneer (tens of metres thick) resting directly on Archean basement. South of the Flack Lake fault, the formation is approximately 1000 m thick and rests disconformably to unconformably on Serpent Formation arenite of the Quirke Lake Group.

Resting directly on the Archean basement below the Dollyberry Formation of the Elliot Lake Group, is commonly one or more of: a variably developed regolith; quartz-pebble conglomerate (Photo 1); nearly

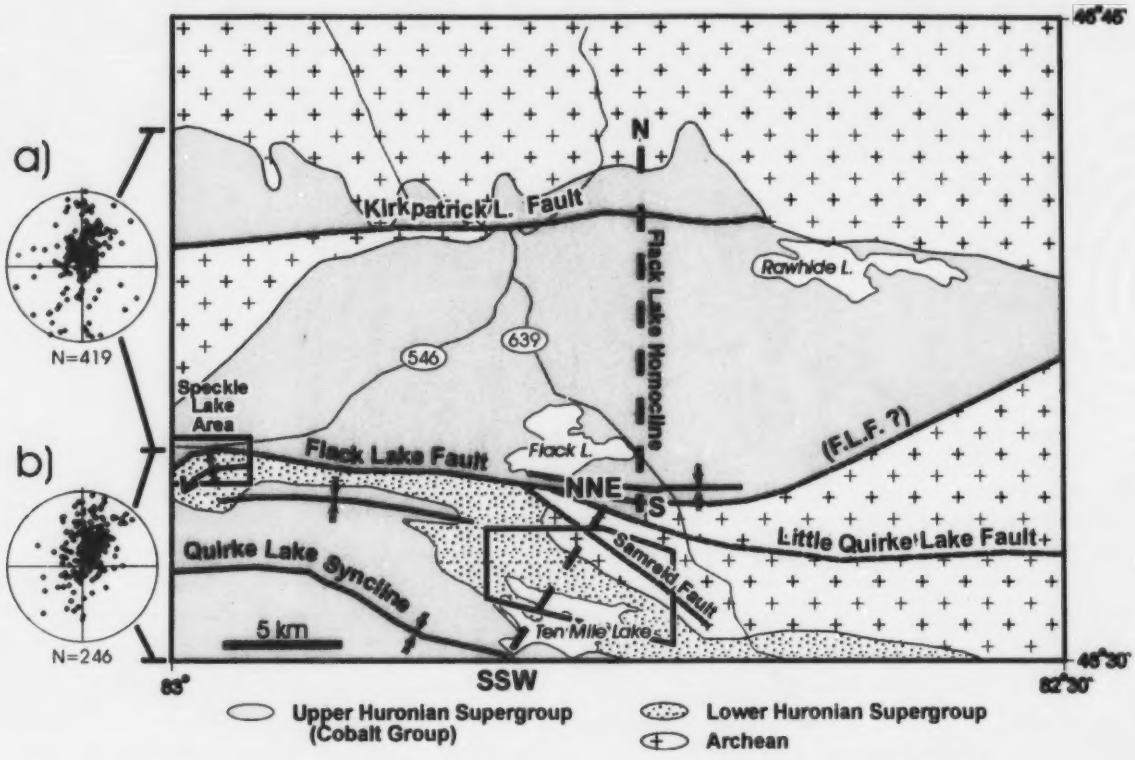

Figure 9. Schematic geology of the Flack Lake area. Note that the eastward extension of the Flack Lake Fault is generally portrayed as the fault indicated "F.L.F."; alternatively, Little Quirke Lake Fault might be the eastward extension. Stereonet (a) is based on bedding measurements from north of the Flack Lake Fault and indicates strata are generally dipping 10° to the south. Steeper dips are from folded strata adjacent to the Flack Lake Fault. Stereonet (b) is based on bedding measurements from south of the Flack Lake Fault and indicates that regional folds are plunging very shallowly to the west-northwest. Dashed lines N–S and NNE–SSW indicate the positions in the section shown in Figure 8. Boxes on the left and in the centre indicate the Speckle Lake (Figure 13) and Ten Mile Lake (Figure 10) areas, respectively.

monolithic matrix-supported to clast-supported "conglomerate" (Photo 2) with quartz-eye matrix; and a quartz-grit wacke (*see also* Bennett 1978). Locations of these features are shown in Figure 10. One relatively large area of conglomerate lying beneath the Dollyberry Formation, previously unmapped, was discovered in this study near the newly identified Samreid fault (Figure 10). This conglomerate was originally assigned to the Dollyberry Volcanics (and is shown as part of that unit in Figure 10); however, the conglomerate and associated wacke may represent Livingstone Creek Formation units (G. Bennett, personal communication, 1997).

An important observation in the Flack Lake area is that the basal Ramsay Lake Formation conglomerate of the Hough Lake Group lies, with marked angular discordance, on Dollyberry Formation metavolcanic rocks of the Elliot Lake Group (*see* map of Robertson 1961 and Figure 10). East of the area shown in Figure 10, metavolcanic rocks are either not present below the Ramsay Lake Formation, or they are of limited thickness. In the Ramsay Lake Formation conglomerates, numerous metavolcanic clasts and boulders identical to units within the Dollyberry Formation can be found in addition to granitic clasts of the Archean basement.

Photo 1. Quartz pebble conglomerate that rests on Archean basement below the Dollyberry volcanics near southern Bobowash Lake.

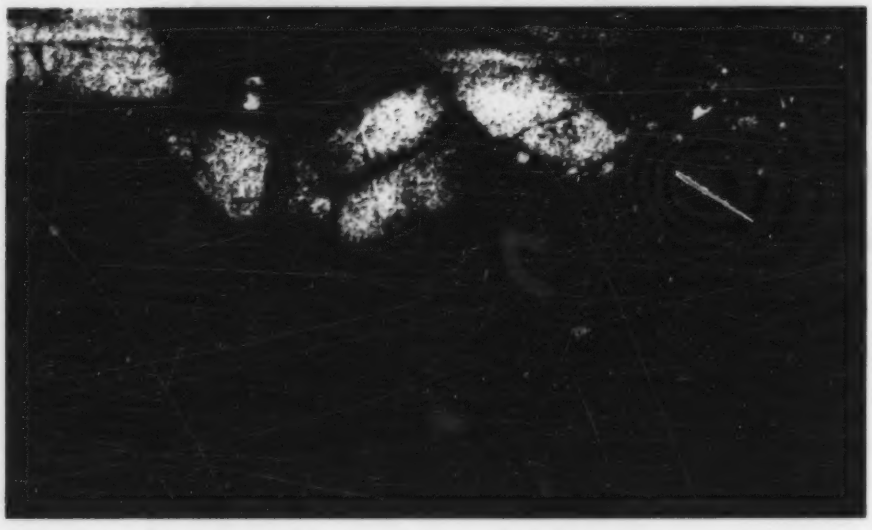

Photo 2. Basal conglomerate consisting largely of Archean granitoid clasts and "regolithic" matrix. Conglomerate underlies Dollyberry volcanics. Photo from southern Dollyberry Lake.

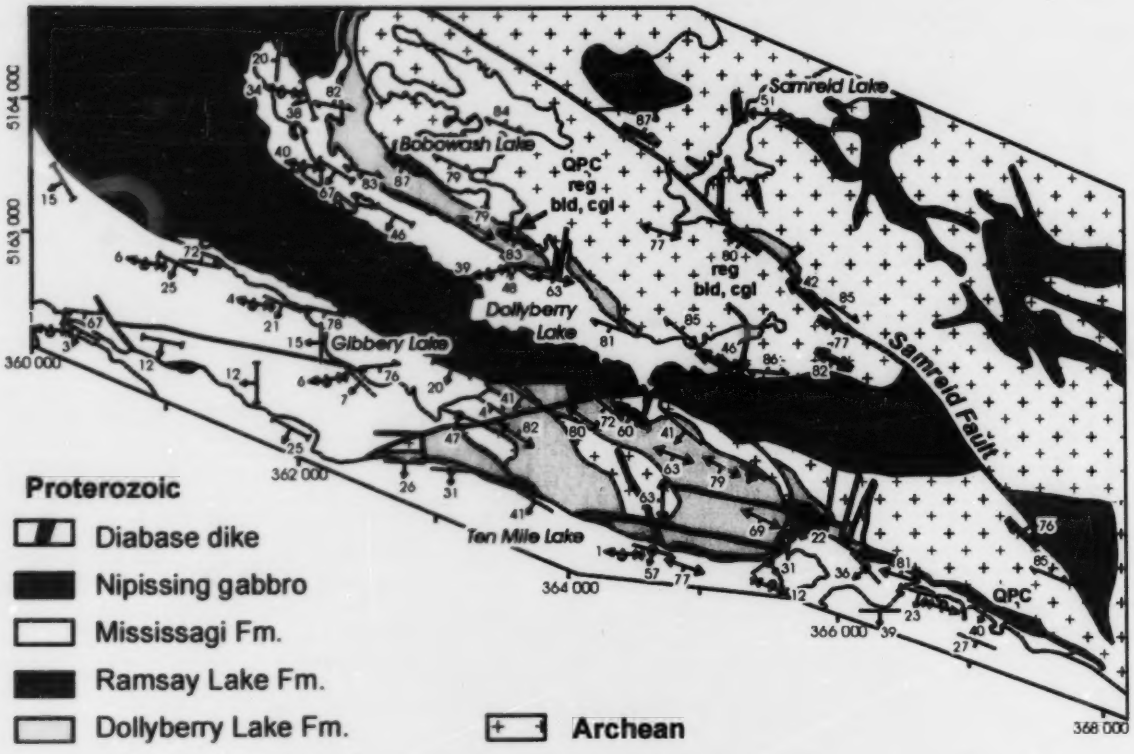

Figure 10. Generalized geology of the Ten Mile Lake area. Cleavage in Huronian Supergroup rocks is generally west-northwest striking. Foliation and shears in Archean basement are also west-northwest striking. Abbreviations: bld, boulders; cgl, monolithic conglomerate; reg, regolith; QPC, quartz pebble conglomerate. Symbols as in Figure 13.

STRUCTURAL GEOLOGY

Fabrics

Rocks from the Flack Lake homocline generally do not possess tectonic fabric, except where in close proximity to faults (Figure 11a). South of the Flack Lake fault, a weak to moderate cleavage can be identified in many rocks (Figure 11b). In the Ten Mile Lake area (Figure 10), a weak to moderate foliation strikes west-northwest and has a line of intersection with bedding that is approximately parallel to the pole of the great circle to bedding plane poles (Figure 12). This relationship is consistent with the cleavage having formed synchronously with folding.

In the Speckle Lake area (Figure 13), cleavage is generally subparallel to the axial trace of folds and the trace of the Flack Lake fault. Bedding–cleavage intersections and fold axes plunge shallowly. In the Espanola Formation, siltstone layers in carbonate-rich metasediments are boudinaged (Figure 11c). Boudin axes plunge parallel to the minor folds and indicate subvertical extension in the plane of the axial surface. Cumulatively, the fabric relationships suggest that folding and cleavage formation were synchronous, that they likely formed during compression, and that they were linked to displacement on the Flack Lake fault.

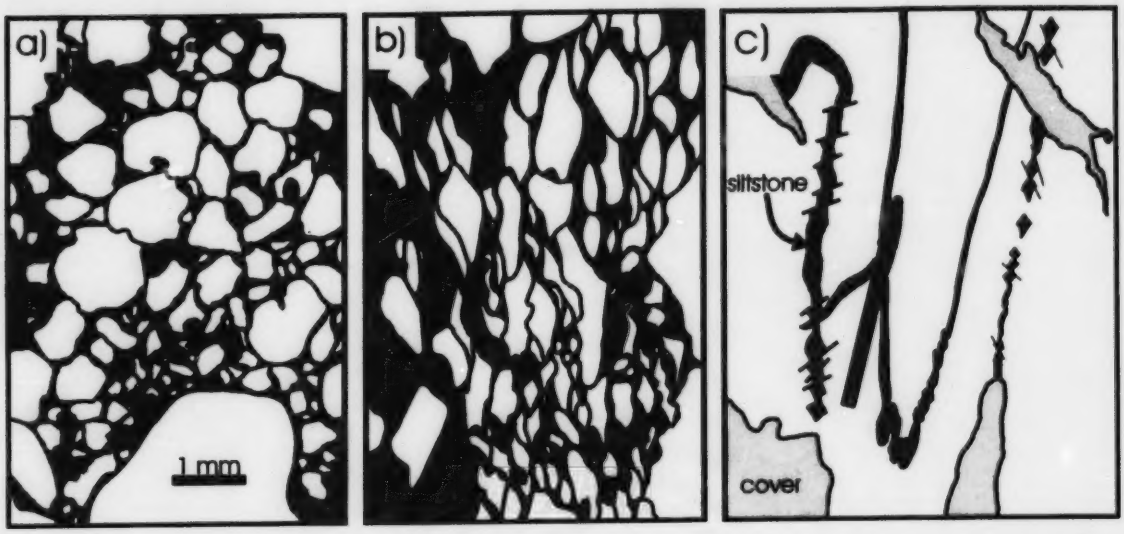

Figure 11. a) Unstrained quartz grains in sandstone north of the Flack Lake Fault. Line drawing from thin section. b) Strained quartz grains in sandstone from south of the Flack Lake Fault. Scale as in (a). Line drawing from thin section. c) Folded and boudinaged siltstone layers in Espanola Formation near Speckle Lake.

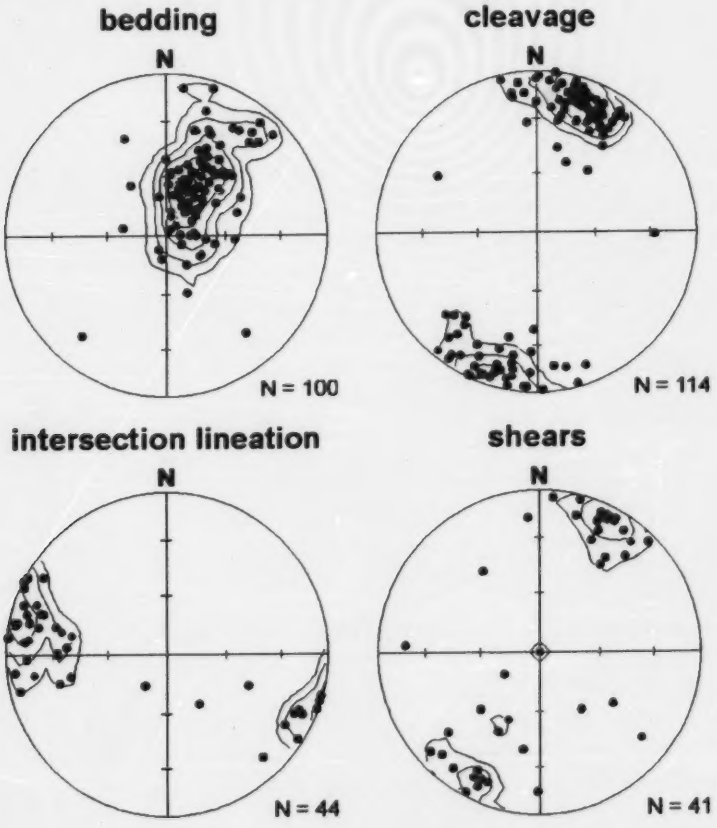

Figure 12. Structural elements of the Ten Mile Lake area. Contours succesively increase in the order 1, 2, 5, 10, 15 and 20% per 1% area.

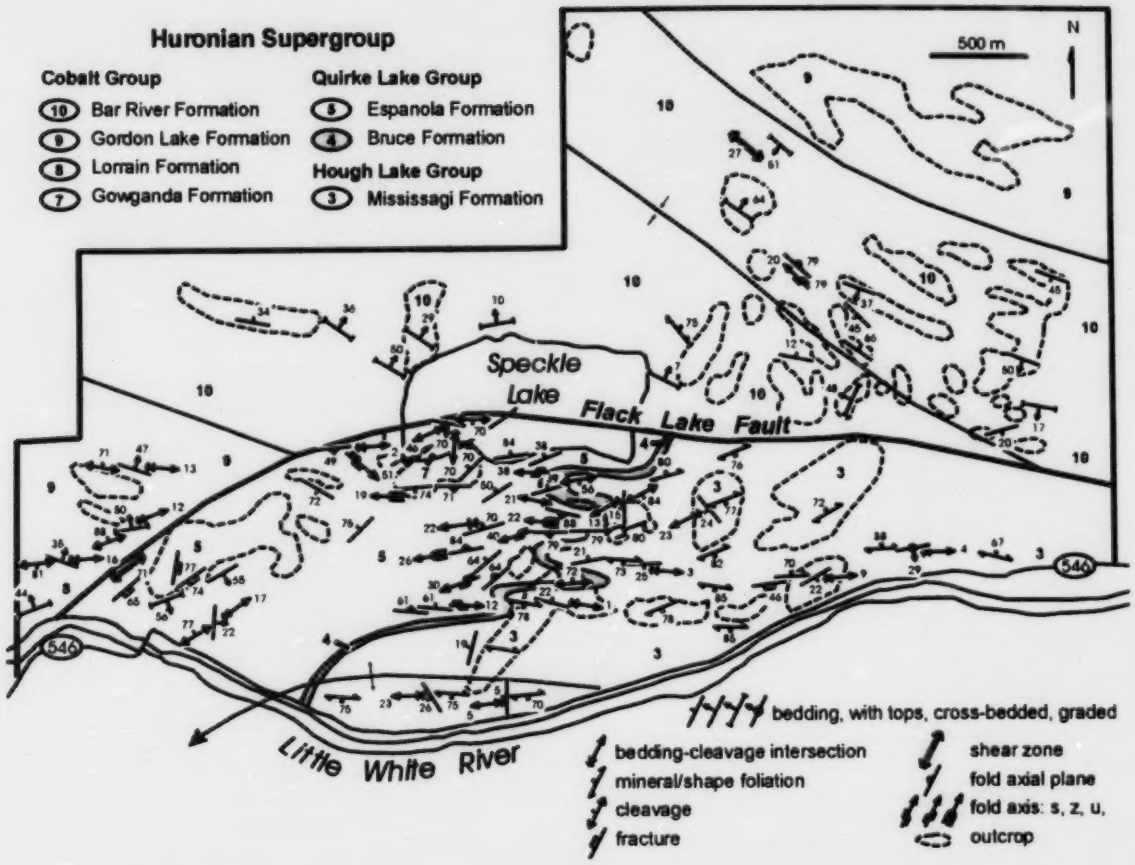

Figure 13. Geology of the Speckle Lake area (see left box in Figure 9 for location). Geology *from* Siemiatkowska (1978) and this study. Hanging wall units located south of the Flack Lake Fault generally possess a weak to moderate, steeply south-dipping, mica/shape foliation that is subparallel to the trace of the fault. Such fabrics are generally absent north of the fault. Also, note parallelism of cleavage and trace of Flack Lake Fault and truncation of fold axial trace north of the fault. Structural relationships are similar to other thrust belts with "footwall synclines" and "hanging wall anticlines".

Faults

The Flack Lake area is disrupted by regional faults including the Kirkpatrick Lake fault, the Flack Lake fault, the Little Quirke Lake fault, and the Samreid fault south of the Little Quirke Lake fault (Figure 9). The variably silicified Samreid fault is northwest striking and extends at least 12 km from Flack Lake to east of Ten Mile Lake. Horizontal exposures indicate a dextral component of shear (Photo 3). Southwest of Samreid Lake, an area of Huronian Supergroup conglomerate was found in the footwall of the fault and Archean basement in the hanging wall. Consequently, the Samreid Fault is interpreted as a dextral-oblique fault with a south-side-up component of displacement.

Numerous, late, dextral, west-northwest to northwest striking faults crosscut the earlier formed structures throughout the Huronian Supergroup in the Southern Province (*see* Giblin et al. 1978; Card and Lumbers 1977). Similar faults are also present in the Flack Lake area, the Samreid fault being an example. Because of their potential relationship to mineralization, these faults are discussed further in "Summary and Discussion" under "NW- to WNW-Striking Faults and Mineralization".

Photo 3. Dextral shear bands from the sheared silicified Samreid fault. Photo taken from southern part of fault.

The Flack Lake fault, and spatially associated faults, separate the homocline to the north from the Quirke Lake Syncline to the south. Stratigraphic variations across the Flack Lake fault mentioned above, combined with the juxtaposition of older formations in the hanging wall against younger formations in the footwall, have been used to argue that the fault is an inverted growth fault (e.g., Zolnai et al. 1984). The inferred surface trace of the fault is highly concave to the north (e.g., Roscoe 1969) and would appear to be unusual for a listric growth fault presumed to be down-dropped to the south. The geometry is unusual since most growth faults are concave in the direction of down-dropping; similarly, most thrust faults are, overall, concave toward the hanging wall. Given the number of faults that converge south of Flack Lake (Figure 9), it may be that the Flack Lake fault continues east-southeast from Flack Lake as the Little Quirke Lake fault, rather than to the northeast as has been generally assumed.

Folding and fabric development accompanied formation of the Flack Lake fault. In the Speckle Lake area (Figure 13), the Speckle Lake anticline occurs in the hanging wall of the fault. Footwall synclines also occur adjacent to the fault in the Speckle Lake and Flack Lake areas (Figures 9, 13). In the Speckle Lake area, the axial trace of the hanging-wall anticline is curvilinear and subparallel to the trace of the fault. The fold axis is shallowly, to moderately, doubly plunging. Poor exposure precludes eastward definition of the anticline; however, Nipissing gabbro also defines folds in the hanging wall of the Flack Lake fault that appear to be doubly plunging with an axial trace parallel to the fault (Figure 14).

Structure Section

A schematic structure section, similar to that developed by Zolnai et al. (1984), is illustrated in Figure 15. The section is partially constrained by selected drill hole data (Leahy 1967) located near the line of section. The northern part of the section depicts the gently south-dipping Flack Lake homocline that is truncated by a series of faults presumed to be steeply south-dipping reverse faults that transect the basement–cover interface. Units in the homocline are approximately 10° south dipping; however, just

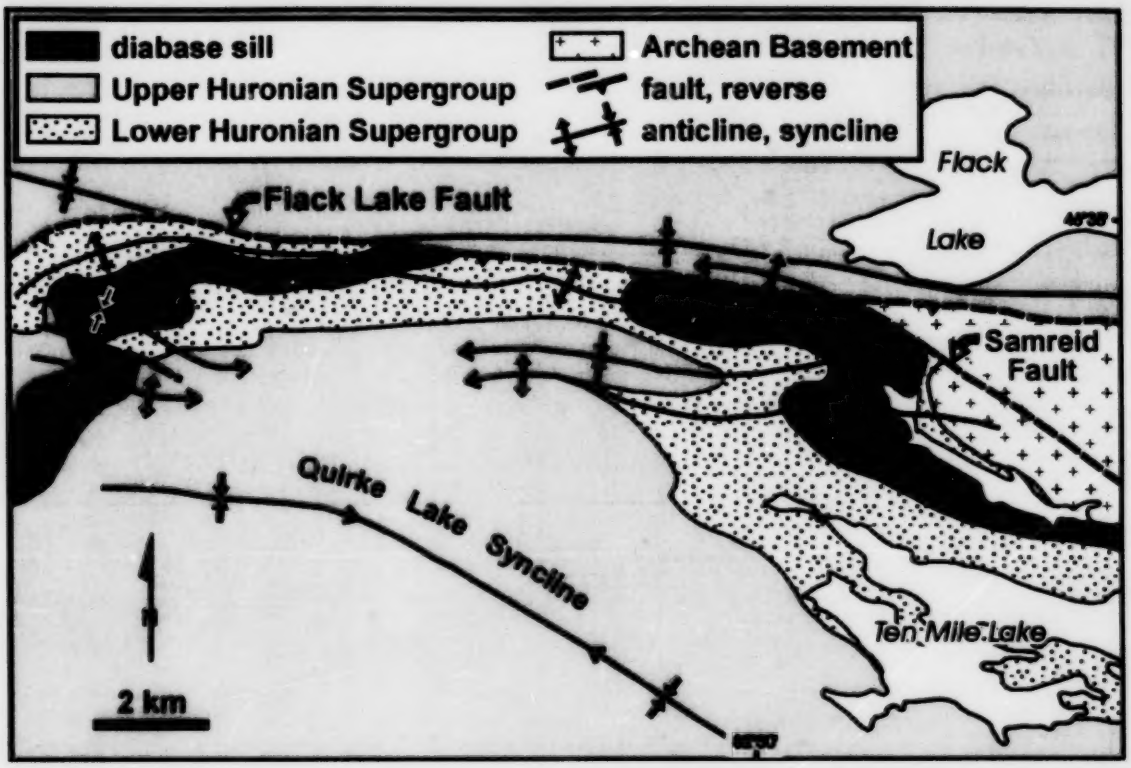

Figure 14. Nipissing gabbro ("diabase sill") folded and faulted in a style similar to that of host rocks suggesting that the regional folding and faulting postdates 2.22 Ga, the age of Nipissing gabbro.

north of the fault, tight folding has locally resulted in steeper dips. Strata in the Quirke Lake syncline are generally moderately to shallowly dipping with steeper dips on the north limb of the syncline than the south limb (Figure 15). Several alternative sections could be constructed depending on the orientation assumed for the faults at depth.

As previously indicated by Zolnai et al. (1984), the basement–cover interface appears to be folded with no evidence for a detachment at the interface. Relationships in the Chiblow anticline support Zolnai et al.'s (1984) conclusion. In the Chiblow anticline, Nipissing gabbro (2.22 Ga) cuts the basement–cover interface (e.g., maps of Robertson 1964) with no apparent disruption (Figure 16). This would appear to exclude the possibility of a detachment, at least post-2.22 Ga (age of Nipissing gabbro). This is supported, but not proved, by examinations of the basement–cover interface in the Ten Mile Lake area. Continuous exposures for significant distances along and across this boundary are rare. In several locations stratigraphically below the Dollyberry metavolcanic rocks, there is a weakly deformed to undeformed transition from Archean basement, to regolith, to conglomerate. Domains of shearing within metavolcanic rocks near and parallel to the basement–cover interface are locally present and Archean basement near the interface is locally weakly foliated (Figure 10); however, whether this foliation is Archean or Proterozoic is uncertain. Where kinematic sense could be determined, the sheared domains indicate south-side-up reverse sense of shear. At present, the domains of shear are thought to be local strain heterogeneities focussed at the basement–cover interface, and not indicative of a décollement.

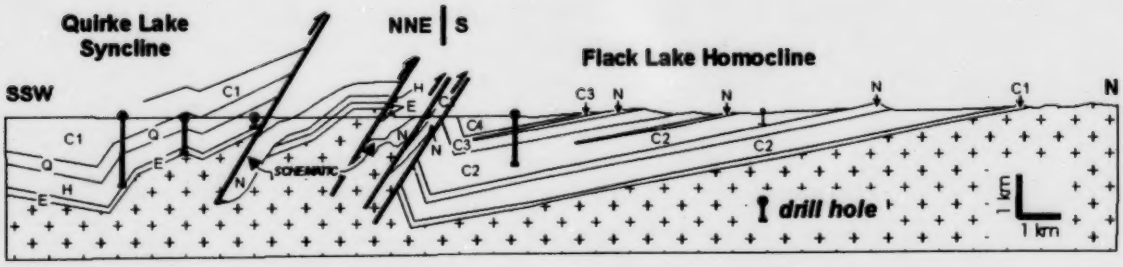

Figure 15. Schematic section located along lines indicated N–S and NNE–SSW on Figure 9. Section based on surface dips and drill hole data. Dip of faults is assumed and deep part of section is under southern part of Flack Lake Homocline is schematic. Section is largely consistent with that of of Zolnai et al. (1984). Note that no Lower Huronian formations are present north of the Flack Lake Fault and that the Gowganda Formation is considerably thicker south of the Flack Lake Fault. "N" represents Nipissing gabbro; all other abbreviations as in Figure 8.

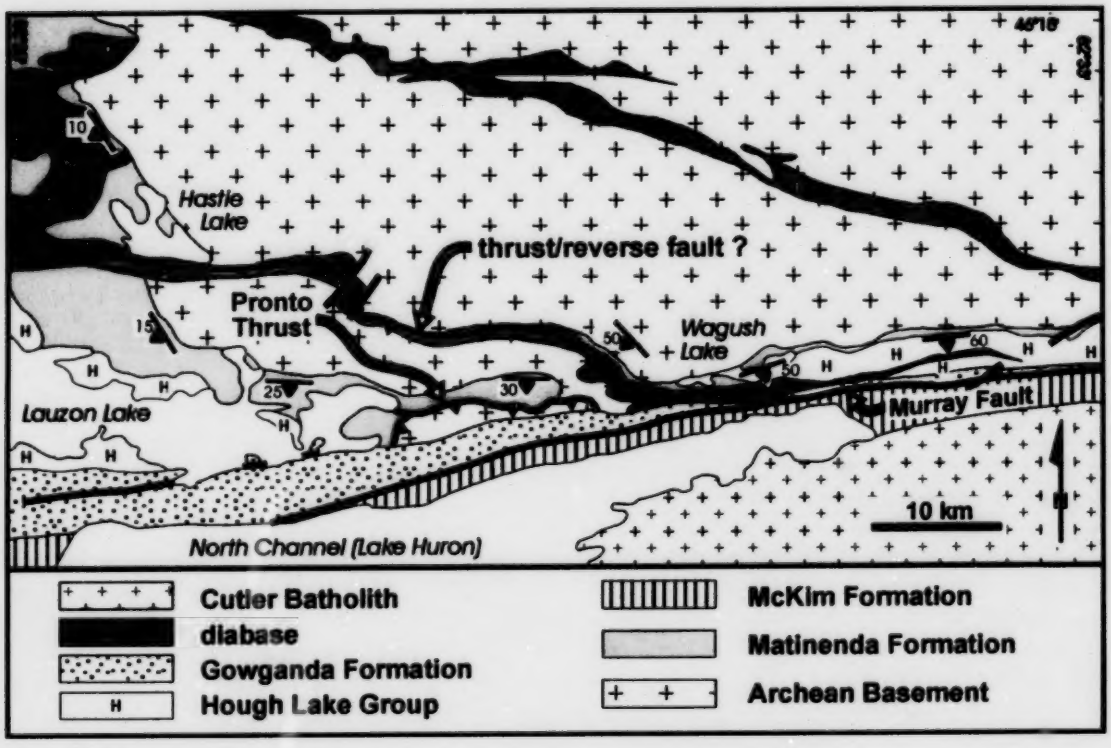

Figure 16. Geology of the Lauzon Lake area (*modified from* Robertson 1964) illustrating structural repetition of basement–cover contact. The fault labelled as "thrust/reverse fault" is not indicated on Robertson's map. This fault is interpreted based on the offset of the basement–cover contact near Hastie Lake and the repetition of the basement–cover contact near Wagush Lake. Nipissing gabbro appears to have been emplaced along this fault thereby indicating pre-2.22 Ga deformation. Note that Nipissing gabbro is not displaced along the basement–cover interface. This implies there is not a detachment between the basement and the cover in the Chiblow Anticline area subsequent to emplacement of Nipissing gabbro.

May Township Area

STRATIGRAPHIC RELATIONSHIPS

This section on stratigraphic relationships is largely summarized from the map of Robertson and Siemiatkowska (1971). The May Township Area is underlain by lower Huronian strata of the Elliot Lake and Hough Lake groups (Figure 17) (Robertson and Siemiatkowska 1971; Jackson et al. 1993); Archean granitoid basement occupies the northwest portion of the township. The Murray fault, like the McMahon Lake faults and the Flack Lake fault in the Aberdeen and Flack Lake areas, respectively, demarcates some significant differences in stratigraphy. The most pronounced difference is in the apparent thickness of the McKim Formation. North of the fault, at the current level of erosion, the formation is only tens of metres thick; however, south of the fault the formation likely exceeds 1000 m. North of the Murray fault, Elliot Lake Group strata are present and include Salmay Lake Formation metavolcanic rocks, and metasedimentary rocks of the Matinenda and McKim formations. South of the fault, the Elliot Lake Group is represented by only the McKim Formation; formations stratigraphically below the McKim Formation and Archean basement are not observed at surface south of the Murray fault.

STRUCTURAL GEOLOGY

Regional Structure

The dominant structural grain of the May Township area is east-northeast, which contrasts with the Aberdeen and Flack Lake areas where the structural grain is west-northwest. There are, however, some west-northwest-striking faults and folds present in May Township (Figure 17). The east-northeast-striking structures, including the Murray fault, predate the west-northwest-striking ones. The Spanish River fault is inferred on the basis of a low topographic lineament and separation of two different structural domains (*see below*).

Although the overall structural pattern is relatively simple, four structural domains can be recognized in the area (Figure 18). The northern part of the map area comprises Domain 1 and consists of Archean granitoid basement. Steeply dipping strata of the Lower Huronian Supergroup between the basement and the Murray fault are assigned to Domain 2. Domain 3 is situated between the Murray and Spanish River faults and includes McKim Formation metasediments and Nipissing gabbro that together are multiply folded. Domain 4 is south of the Spanish River fault and consists of Hough and Quirke Lake group strata preserved along the north limb of a syncline. Late, west-northwest-striking dextral faults crosscut the structural domains and the Murray fault. These faults are discussed further in "Summary and Discussion" under "NW- to WNW-Striking Faults and Mineralization".

Structural Domains and Fabric Relationships

Domain 1 is in the northwest part of the township (Figure 18) where Archean basement rocks locally have a weakly developed foliation; many outcrops, however, appear massive. The foliation is defined by slightly flattened quartz grains in granitoid rocks and is subparallel to the strike of fabric in adjacent Huronian rocks.

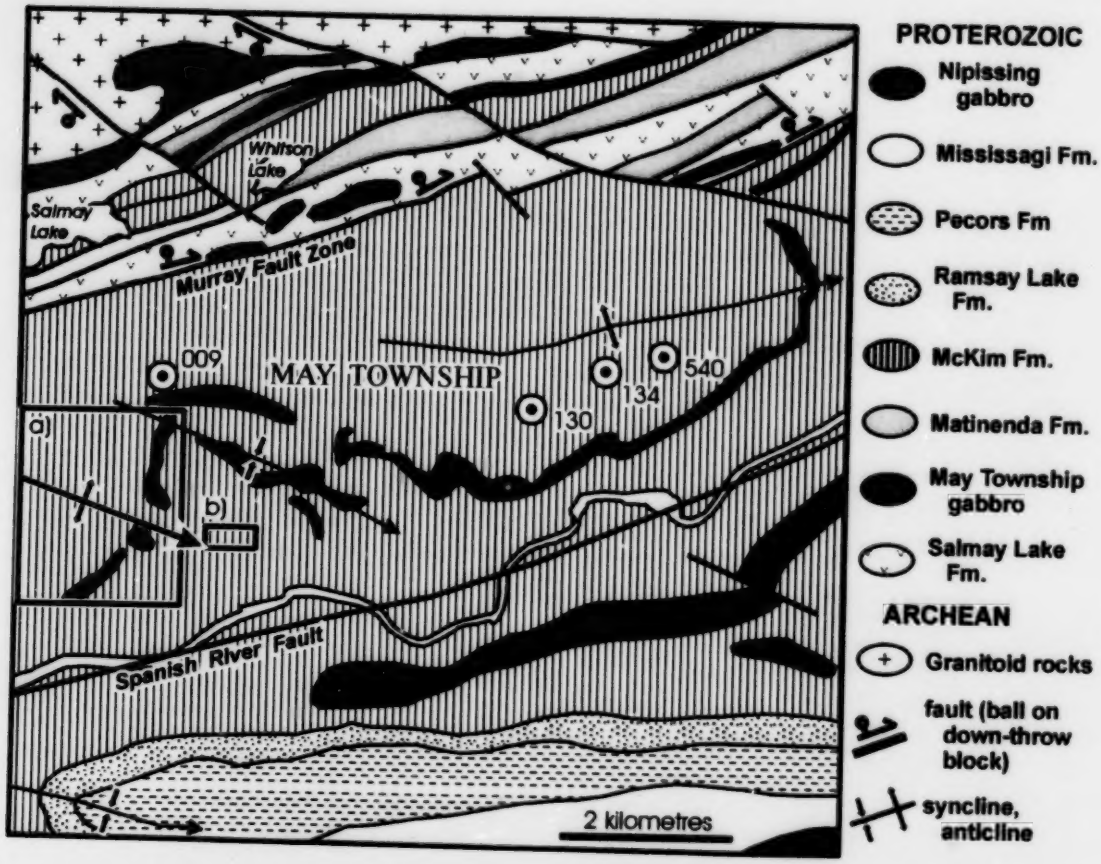

Figure 17. General geology of the May Township area (*modified from* Robertson and Siemiatkowska 1971 and Jackson et al. 1993). Boxes labelled "a" and "b" locate the areas shown in further detail in Figures 21 and 23, respectively. Numbers correspond to samples analyzed for pressure–temperature determinations (Figure 28).

Domain 2 is located between the Archean basement and the Murray fault (Figure 18). In this domain, bedding is generally steeply dipping, south facing, and east-northeast striking with a subparallel mineral foliation or cleavage, or both (Figure 18). Preliminary thin section observations show that the steeply dipping cleavage, at least locally, is a late fabric superimposed on an earlier mica foliation.

Domain 3 lies between the Murray fault and the Spanish River fault (Figures 17, 18) and is underlain by the McKim Formation. Structural patterns for this domain are summarized in Figure 19. Bedding in this domain is generally shallowly dipping (Figure 18). A well-developed mica foliation is the earliest recognizable tectonic fabric and is commonly oriented either at a low angle or subparallel to bedding (Photo 4). Smaller gabbro bodies and the margins of large gabbro bodies are commonly foliated parallel to the foliation in the surrounding metasedimentary rocks. Locally, the early mica foliation is axial planar to folds of bedding. Outcrop-scale folds with axial planar mica foliation are rare, one such fold is depicted in Figure 20. Small-scale folds of quartz veins, pegmatitic veins, and bedding accompanied by a penetrative axial planar mica foliation are, however, common (Figure 19b). These folds are commonly tight to isoclinal and, locally, rootless. Also common within the plane of the foliation are boudinaged competent units such as quartz veins (Photo 5), granitoid veins (uncommon) (Photo 6), and metagabbro units. These small-scale structures indicate that high ductile strain occurred during development of the mica foliation in Domain 3.

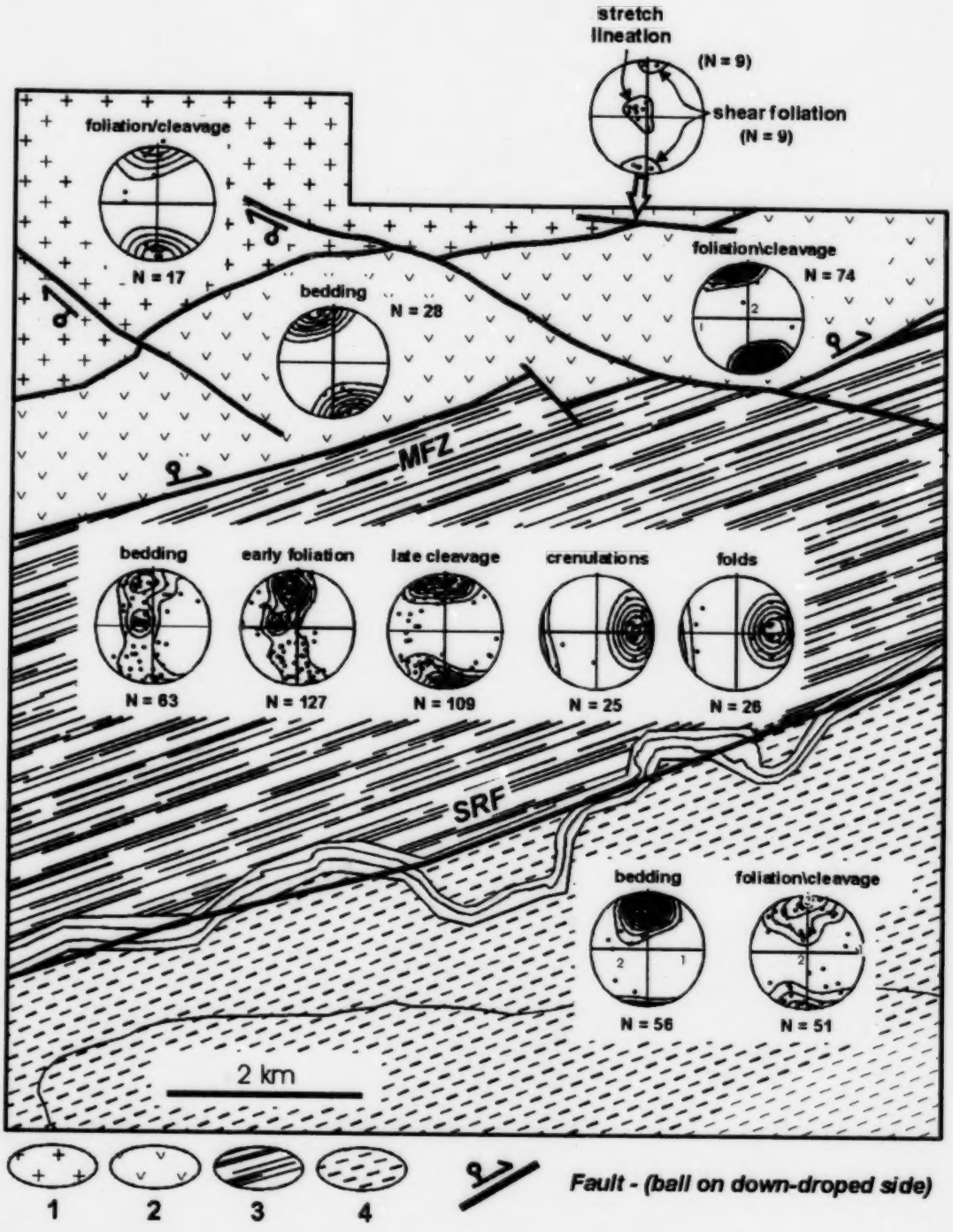

Figure 18. Generalized structural domains of the May Township area. Domain 1 is Archean basement; Domain 2 is steeply dipping strata located between Archean basement and the Murray Fault zone; Domain 3 includes mostly McKim Formation between the Murray Fault zone and the inferred Spanish River fault; Domain 4 is located south of the inferred Spanish River fault. Figure is based on the map of Jackson et al. (1993).

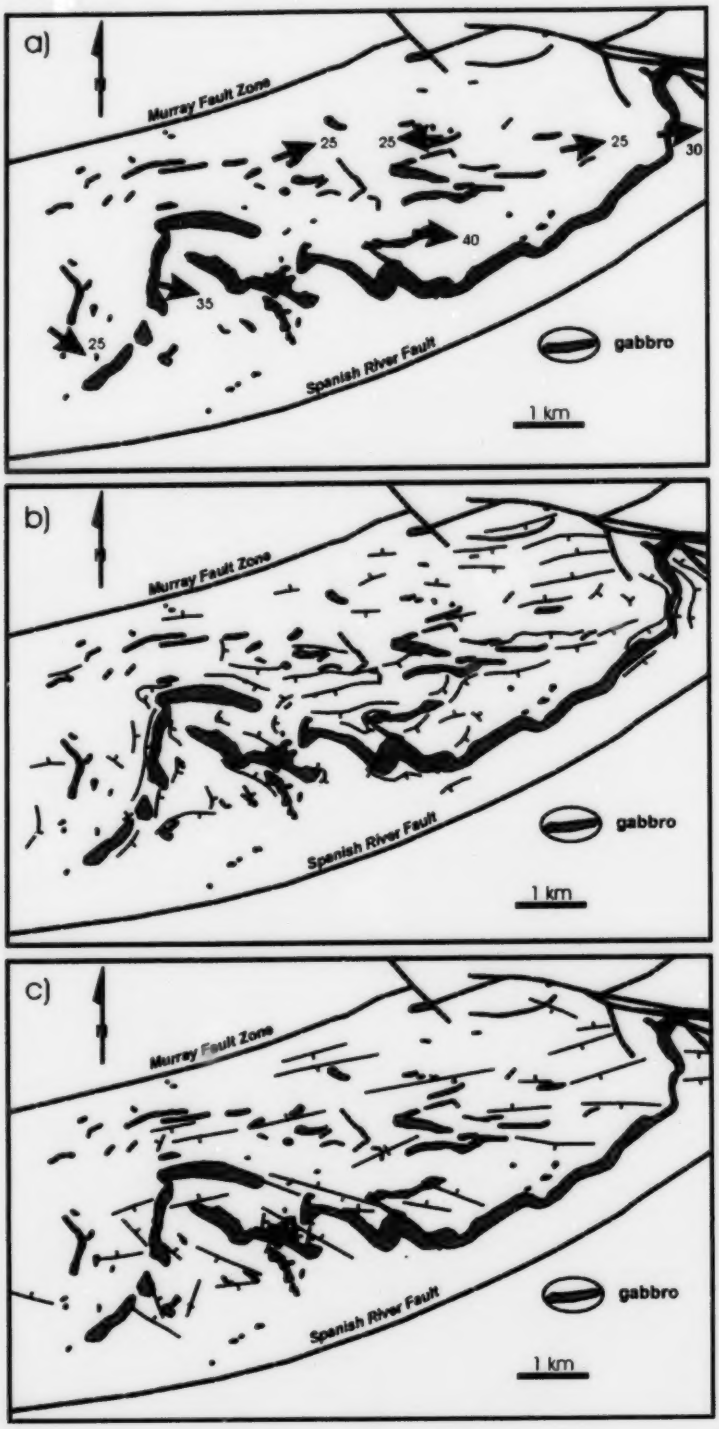

Figure 19. Schematic lineation and foliation maps of the McKim Formation from structural Domain 3 in Figure 18. a) Generalized fold and crenulation plunges. b) Mica foliation trajectories. c) Crenulation cleavage trajectories. Note that trajectories in (b) are generally shallow to moderately dipping and subparallel to bedding, whereas those in (c) are steeply dipping and are subparallel to the traces of regional folds.

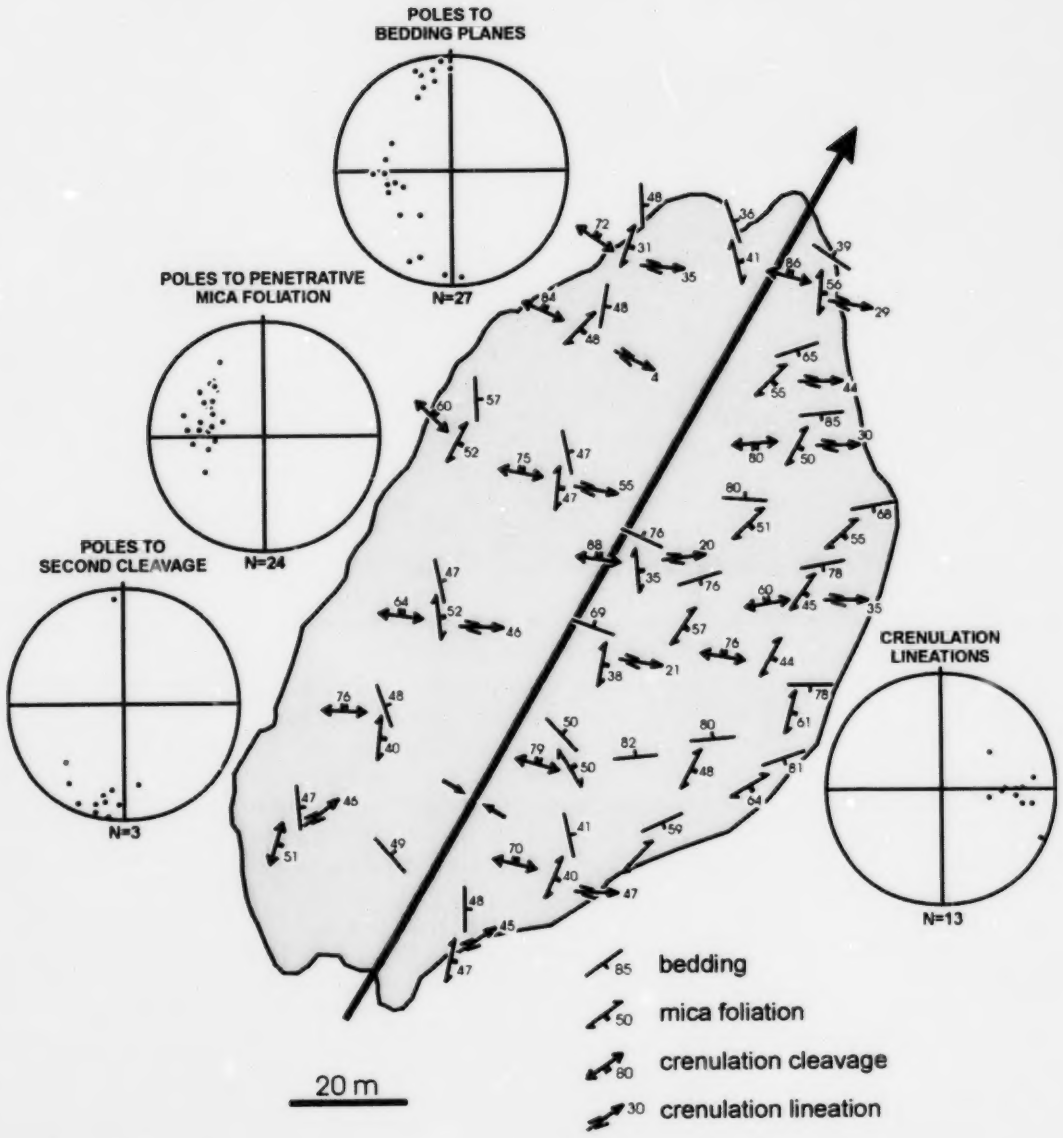

Figure 20. Example of large-scale fold with mica foliation parallel to axial trace. Fold and parallel foliation are transected at a high angle by later crenulation cleavage. Outcrop is from the southwest portion of Figure 21. Stereonets summarize orientation of structural elements.

On a regional scale, bedding, the early mineral foliation, and metagabbro bodies are subparallel (Figures 19). These structural elements are refolded (Photo 7) and overprinted by a second or "late" spaced cleavage to crenulation cleavage. The folds and associated late cleavage are generally east-northeast striking, but are also west-northwest striking. The two different orientations may represent separate generations of structures, or they may be part of a conjugate set of folds (e.g., Card 1963). At several locations in May Township, west-northwest striking cleavage overprints east-northeast striking cleavage; however, extrapolating this observation to similarly oriented fold sets is tenuous.

Photo 4. McKim Formation wacke-pelite showing bedding (S_0) with low angle foliation (S_1) that is overprinted by crenulation cleavage (S_2). S_2 is axial planar to map-scale folds. Photo from May Township.

Photo 5. Isoclinally folded and boudinaged quartz veins. S_1 is axial planar to folds. Photo from May Township.

Photo 6. Isoclinally folded and boudinaged pegmatitic material. Photo from May Township.

Photo 7. Gently plunging fold of bedding and subparallel penetrative mica foliation. Photo from May Township.

The structural pattern of Domain 3 is dominated by the large antiform delineated by metagabbro (Figure 17). In general, the fold axial trace strikes east-northeast, however, there are also west-northwest-striking folds of metagabbro (Figure 19) that might simply be parasitic folds on the larger scale antiform. Viewed in this light, the fold sets mentioned above may be roughly coeval.

Two areas mapped in detail illustrate the general fabric relationships for structural Domain 3. The area illustrated in Figure 21 reveals northerly striking bedding and subparallel penetrative mica foliation folded about later east-southeast-striking, upright, shallowly plunging folds that are associated with a crenulation cleavage (structural elements are summarized in Figure 22). Mica foliation is commonly accompanied by boudinaged and folded quartz veins, and locally by boudinaged gabbro bodies. Although the bedding and mica foliation are nearly subparallel, it is commonly possible to distinguish a small angular relationship between the two (Photo 4). The second area mapped in detail shows similar fabric relationships (Figure 23), although fabric orientations differ. For the area indicated in Figure 23, mica foliation is again oriented at a low angle to bedding, and a second crenulation cleavage is present. Here, the late cleavage is generally west-northwest striking rather than east-southeast striking. Structural elements for this outcrop are summarized in Figure 24.

At one outcrop (Figure 20) from the south end of the area illustrated in Figure 21, the penetrative mica foliation is axial planar to folded strata and the late cleavage cuts across the outcrop at a high angle to both bedding, the fold axial trace, and foliation. Such exposures are rare, but indicate that some relatively large folds formed during development of the penetrative mica foliation.

Fabric orientations (Figure 22) for the area of Figure 21 indicate the following: bedding and mica foliation are generally subparallel; cleavage is generally east-southeast striking and steeply dipping; and crenulations, calculated bedding–cleavage intersections and cleavage–foliation intersections, and the pole to the great circle of bedding plane poles are all coaxial. Regional data reflect similar relationships (Figure 18). The coaxial nature of the linear elements can be explained several ways. 1) Folding associated with early penetrative mica foliation and subsequent folding associated with the late cleavage were coaxial. 2) No substantial large-scale folding of bedding occurred during formation of the penetrative mica foliation and the coaxiality simply results from nearly coplanar features being folded together. In this scenario, most of the reorientation of bedding is a result of the folding associated with the late cleavage. 3) Yet another explanation is that large-scale folding associated with the development of the early foliation formed high-amplitude folds with relatively few fold noses (only a few of which may have been recognized in this study (e.g., Figure 20). In this scenario, non-coaxiality of the first and second phase folds and related structural elements might not have been encountered with resultant bias of the data sets. Although additional detailed work is required to choose from the above alternatives, the second alternative is favoured because it does not require fortuitous relationships nor is it based on the absence of data. Furthermore, convincing large-scale nappes or thrust sheets, or both, have yet to be documented in the Southern Province.

Domain 4 is south of the Spanish River fault where bedding is moderately dipping, cleavage is moderately to steeply south dipping, and both bedding and cleavage are east to east-northeast striking. Although the structural database is limited for Domain 4, thin sections and local outcrop observations reveal an early mica foliation that is, at least locally, overprinted by a later steeply dipping cleavage.

Fabrics and the Murray Fault

The trace of the Murray fault in May Township can be inferred from 1) the increase in intensity of steeply dipping cleavage oriented parallel to the fault; 2) the abrupt change in metamorphic grade across the trace of the fault; and 3) a topographic lineament. Thin section and field observations indicate that the steeply dipping cleavage parallel to the Murray fault overprints an earlier mica foliation. Since both the Murray fault and the large antiform in May Township are associated with a cleavage that is similar in relative timing, character, and orientation, it is inferred that at least late movement on the Murray fault and formation of the antiform were coeval.

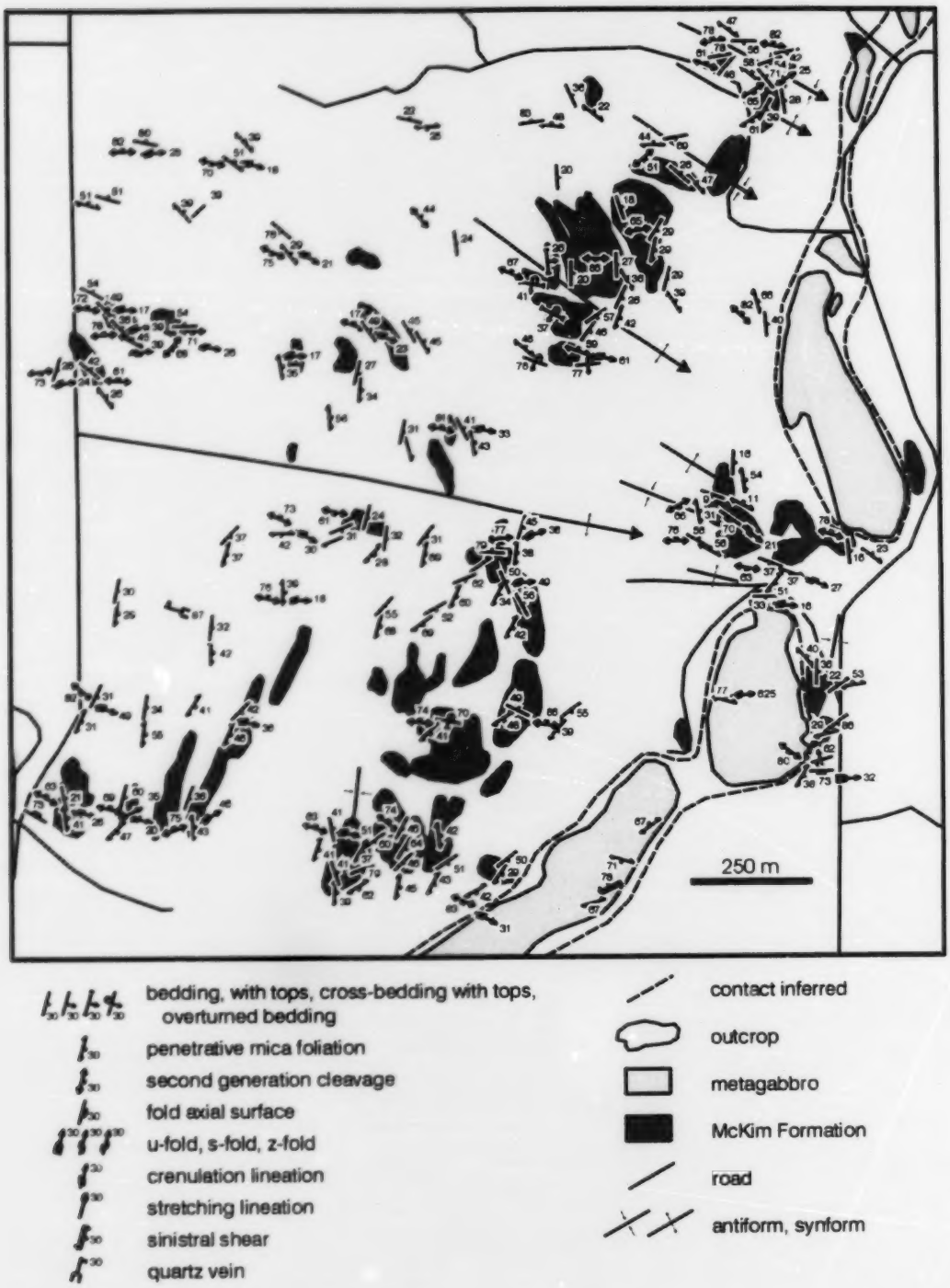

Figure 21. Structural geology of the area indicated by box "a" in Figure 17. Mica foliation is subparallel to trace of units, which are together folded and overprinted by a west-northwest-striking crenulation cleavage and related crenulation lineation. See Figure 22 for structural elements.

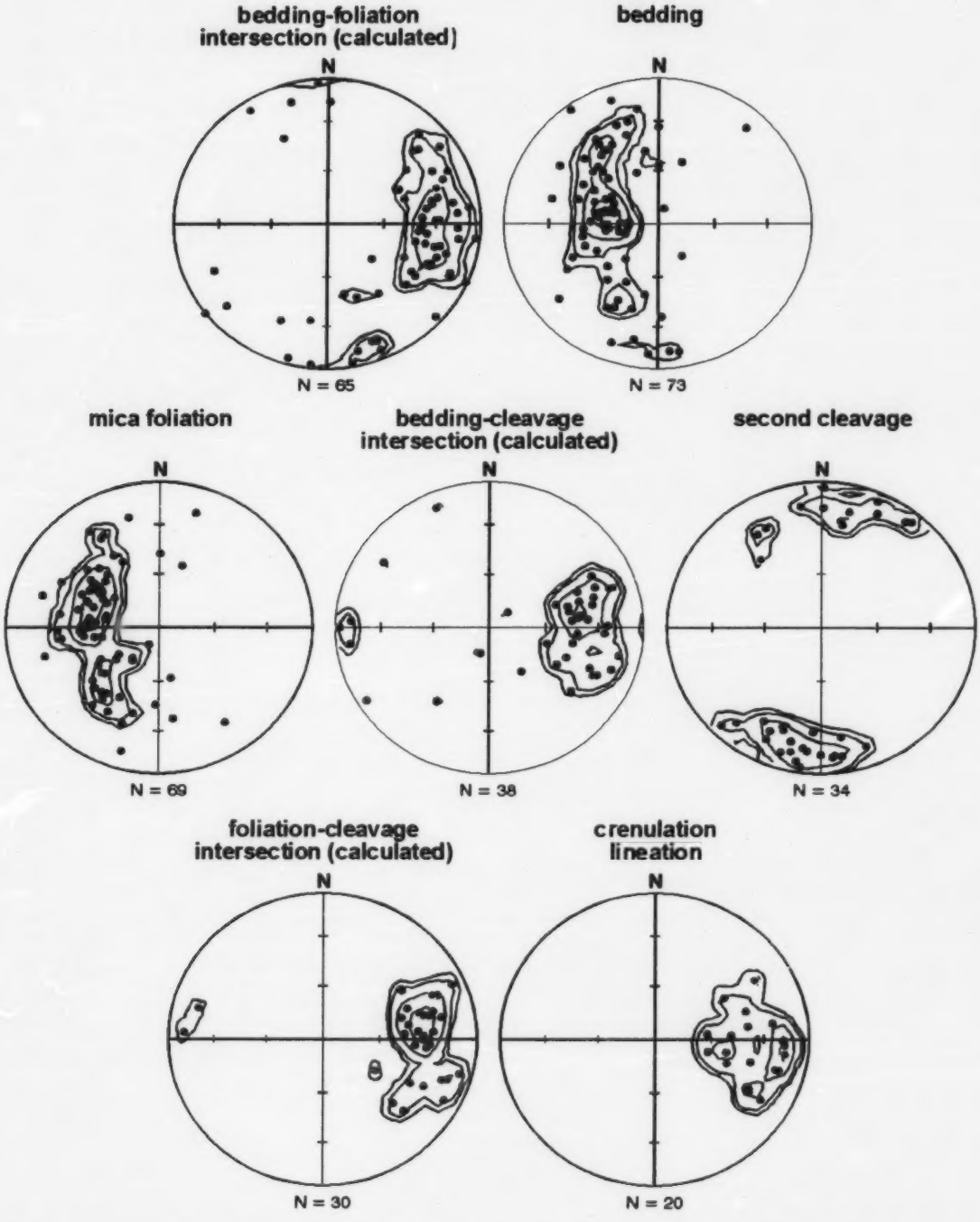

Figure 22. Structural elements of the map area shown in Figure 21. Note that the stereonets indicated as "bedding", "mica foliation", "cleavage" and "crenulation lineation" are all from measured field data, whereas the other stereonets represent calculated values from measured data. Note that bedding and mica foliation are subparallel and that the bedding-foliation and foliation–cleavage intersections are also subparallel. Note also that "cleavage" is generally a second-generation crenulation cleavage and that it strikes west-northwest in contrast to the cleavage from area "b".

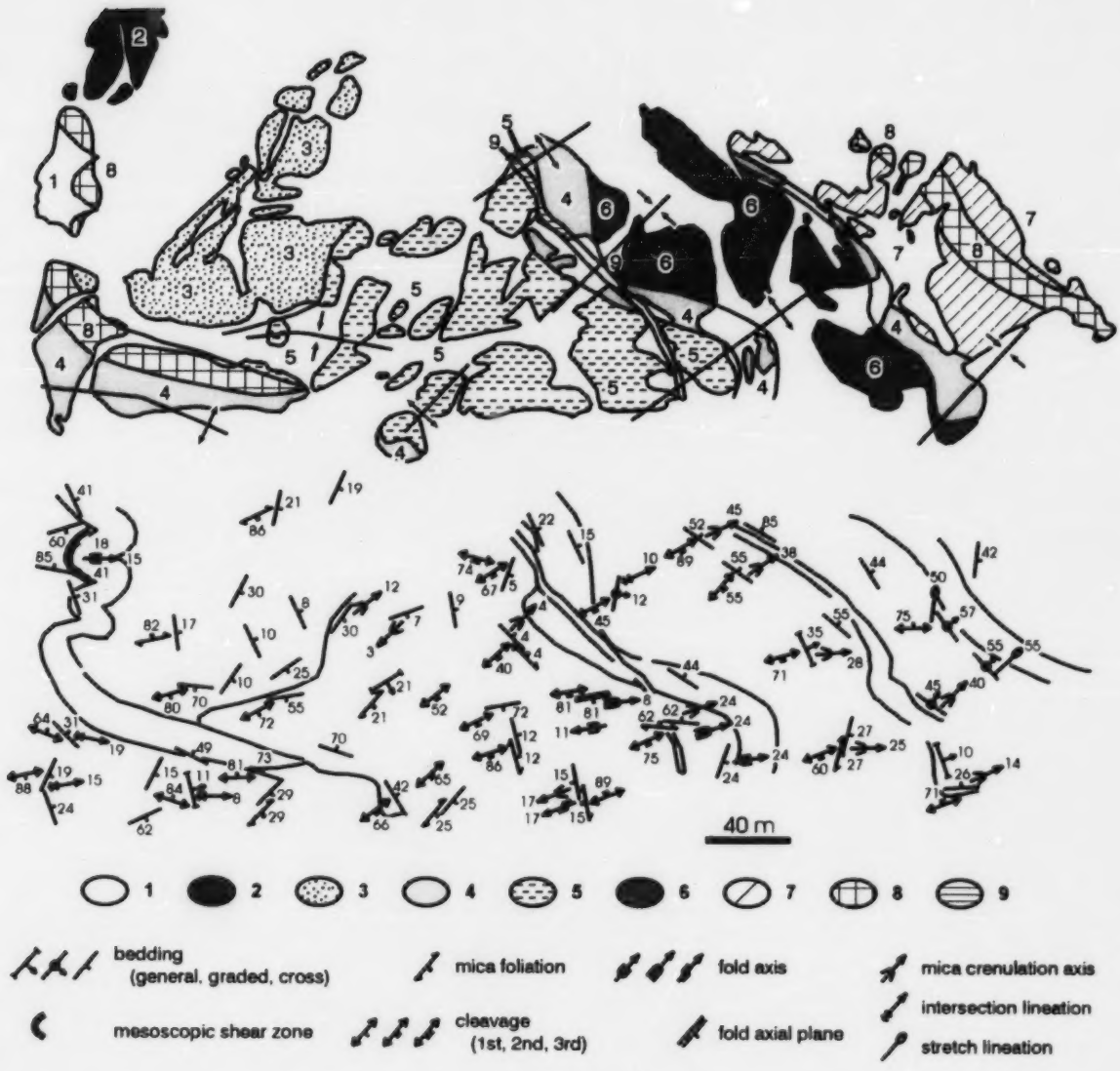

Figure 23. Generalized geology of area "b" shown in Figure 17. Units are as follows: 1) rhythmically layered turbidites; 2) 1 to 3 m thick beds of white-pink weathering crossbedded arkose; 3) 0.5 m thick arkose with thin interbeds of siltstone and pelite; 4) 0.1 to 0.8 m thick beds of white-grey weathering arkose with abundant climbing ripples; 5) pelite; 6) grey to brown weathering ripple cross-laminated wacke–siltstone interbeds; 7) grey to brown weathering graded wacke–siltstone interbeds; 8) gabbro; 9) olivine diabase. Second-cleavage and related folds in this area are generally northeast striking in contrast to the west-northwest-striking folds in area "a" of Figures 17 and 21.

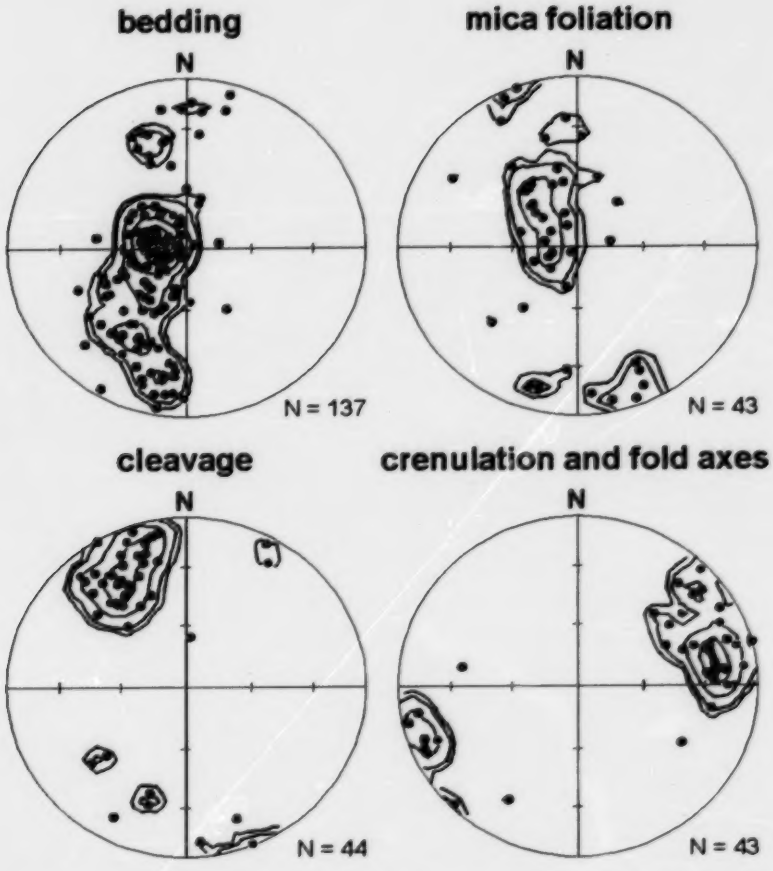

Figure 24. Structural elements of area "b" in Figure 23. Contours are successively 1, 2, 5, 10, 15, and 20% per 1% area.

METAMORPHISM IN THE MAY TOWNSHIP AREA

May Township differs from the Aberdeen and Flack Lake areas in two important respects. Firstly, metamorphic grade is locally of amphibolite facies with staurolite-biotite assemblages in the McKim Formation. Secondly, the structural history is more complex than the other two areas. Relatively high-grade metamorphic rocks in May Township are coincident with the area of greatest structural complexity. Consequently, it is worth considering the metamorphic history of May Township and its relationship to the deformation history. The present report is concerned primarily with structural relationships; therefore, only the main results of studies on coexisting mineral assemblages, mineral chemistry, and *P–T* estimates are presented here.

Metamorphic Zones

Metamorphic grade in May Township increases from chlorite ± biotite grade south of the Spanish River fault to staurolite-biotite grade south of the Murray fault. North of the Murray fault, rocks are again of chlorite ± biotite grade (Figure 25). There is an approximate, although not rigorous, correlation of the metamorphic zones with the structural zones shown in Figure 18. Although metamorphic grade changes

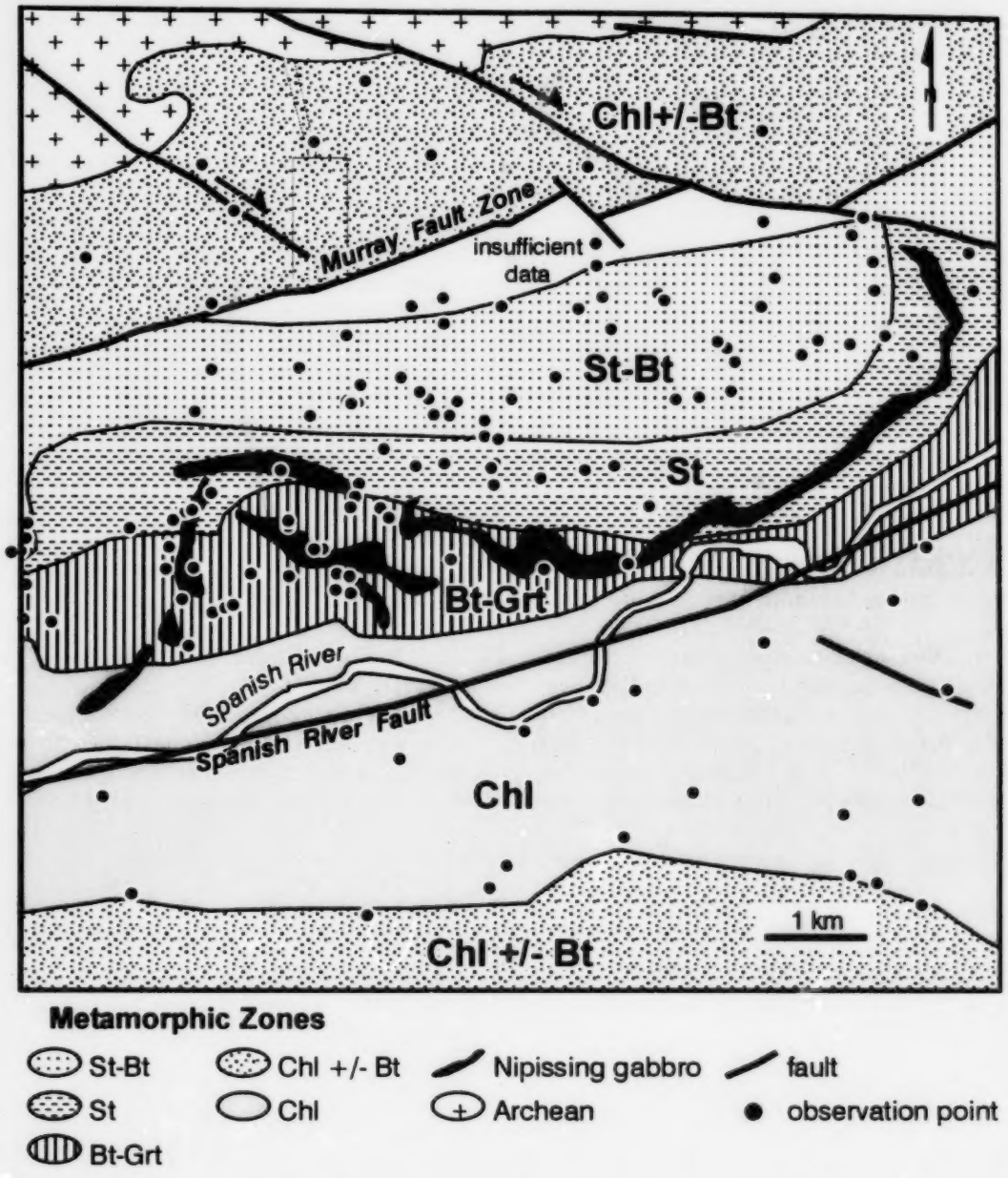

Figure 25. Metamorphic zonation of May Township. Note that the Murray Fault zone juxtaposes the highest grade and lowest grade regions.

abruptly across the Murray fault, poor outcrop in the immediate vicinity of the fault precludes rigorously defining the geometry of the metamorphic zones there. The high-grade staurolite-biotite zone near the fault may either be an elliptical "node" comparable to that defined by Card (1964) or the zone may be truncated by the Murray fault. Elliptical or not, the metamorphic zone boundaries appear to be folded along with the gabbro bodies and trajectories of the early mica foliation (Figure 19); suggesting perhaps that the zone boundaries are subparallel to those structural elements. Consequently, it *may* be valid to

project the trace of these surfaces into a fold-profile. Such a projection (Figure 26) indicates an overall moderate dip of the zone boundaries with steep attitudes on the south limb of the antiform. It is suggested, then, that the elliptical to curvilinear metamorphic zone boundaries mapped in this study and by Card (1964) likely result from folding of originally shallowly dipping metamorphic zone boundaries.

Relative Timing of Metamorphism

Fabric–porphyroblast relationships observed in thin section help constrain the timing of regional metamorphism with respect to deformation. Staurolite porphyroblasts of the staurolite zone generally exhibit inclusion trails of quartz, illmenite, and plagioclase that are straight and continuous with external mica foliation (Figure 27). The porphyroblasts themselves are rotated by the late crenulation cleavage and related folds that postdate the mica foliation. These staurolite porphyroblasts, then, must have crystallized syn- to post-development of the penetrative mica foliation, but prior to formation of the crenulation cleavage. In some of the highest grade rocks from the staurolite-biotite zone, inclusion trails within garnet and staurolite porphyroblasts are curvilinear, concentric, or spiral in shape (Figure 27) indicating that these porphyroblasts grew synchronously with formation and rotation, or deflection, of the early mica foliation. Later crenulation cleavage comparable to that from the lower grade metamorphic zones is also present and postdates the porphyroblasts. Consequently, some porphyroblast growth in the highest grade rocks occurred synchronously with development and rotation of the penetrative mica foliation, but prior to the development of the late crenulation cleavage and related folds.

Another important observation concerning the relative timing between metamorphism and deformation is the relationship between late cleavage and retrograde chlorite that replaces garnet porphyroblasts. Figure 27 shows retrograde chlorite and sericite replacing garnet. Matrix mica in this rock exhibits a well-developed penetrative mica foliation that is crenulated. The retrograde chlorite is affected by the same cleavage that crenulates the matrix. Many garnet porphyroblasts exhibit this relationship. The significance of these observations is that the large-scale folds south of the Murray

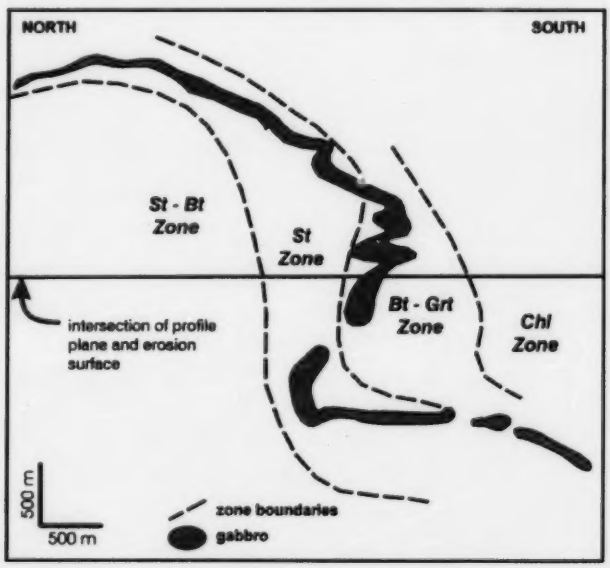

Figure 26. Schematic projection of metamorphic zones onto a plane perpendicular to the general east-northeast plunging lineations. Plane is striking south-southwest and dipping 20° to the west-northwest.

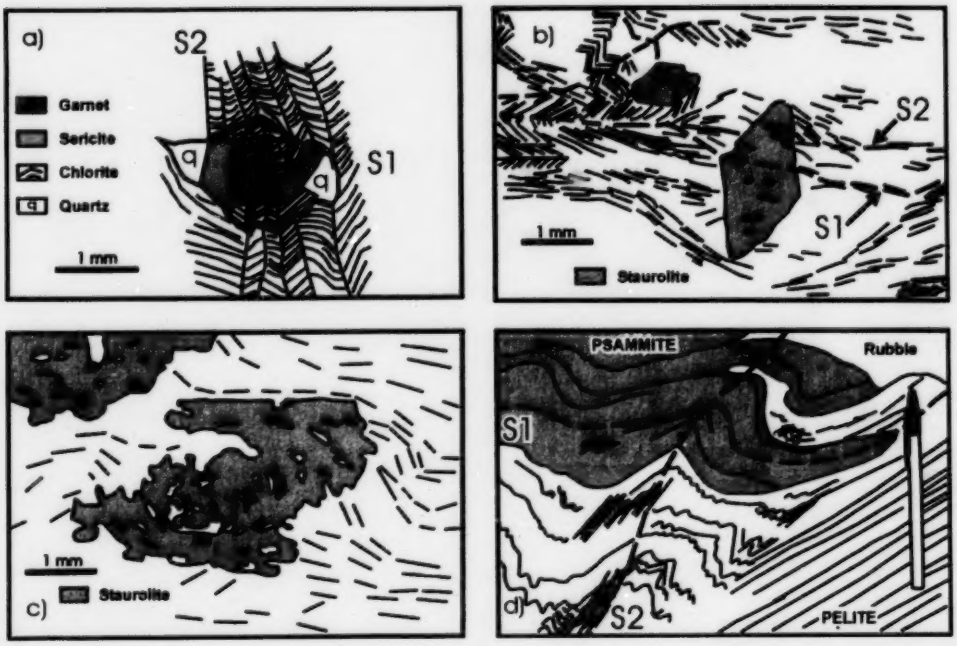

Figure 27. Fabric relationships in McKim Formation metapelites. a) Retrogressed garnet porphyroblast. Quartz-beards are developed in S_1-related strain shadow of porphyroblast. Garnet is retrogressed to fine-grained sericite and coarser chlorite. The chlorite grains are crenulated by the same crenulation that affects the S_1 mica foliation in the matrix of the rock. This suggests that retrogression postdated S_1 and predated S_2. b) Staurolite porphyroblasts with straight quartz inclusion trails that are continuous with external S_1 mica foliation. S_2 crenulation rotated staurolite porphyroblasts and crenulated S_1 mica foliation. Staurolite crystallization was syn to post S_1 and pre S_2. c) Staurolite porphyroblast with curved inclusion trails that are continuous with curved mica foliation in matrix of rock. Staurolite is inferred to have crystallized syn- to post-rotation of the mica foliation. d) S_1 penetrative mica foliation axial planar to subhorizontal folds of bedding and later steeply dipping S_2 crenulation cleavage.

fault that are associated with axial planar crenulation cleavage not only postdate peak metamorphism, but they also postdate retrogression and cooling of peak metamorphic assemblages. This implies a significant time interval between peak metamorphism and the regional folds associated with crenulation cleavage.

Metamorphic Conditions

Based on the distribution of aluminosilicate polymorphs in Huronian metasedimentary rocks, regional metamorphism occurred at relatively low pressures (e.g., Card 1978b; Church 1967). In low-grade rocks north of the Murray Fault, andalusite is reported (Wood 1973). In low-grade rocks of the Whitefish Falls area, well south of the Murray fault, kyanite and andalusite are stable (Church 1967; Card 1978a, 1978b). In high-grade rocks south of the Agnew Lake area, Fox (1971) reports andalusite in staurolite-grade rocks. In somewhat higher grade staurolite-biotite-bearing rocks located west of May Township, the author has found sillimanite in staurolite-biotite-bearing rocks. The "metamorphic field gradient", then, represents a low-pressure facies series from kyanite to andalusite to sillimanite. Speculatively, the highest grade rocks were metamorphosed at pressures below the aluminosilicate triple point.

In order to test the above conclusion, metamorphic pressure and temperature were calculated for 4 samples from May Township. The samples are all from relatively high-grade rocks from south of the Murray fault. Details of the calculations, mineral-assemblages, and tables of mineral analyses will be

presented elsewhere; only the results are summarized here. The equilibria used in calculating metamorphic pressure and temperature for all 4 rocks were:

phlogopite + almandine = annite + pyrope (garnet-biotite Fe-Mg exchange reaction) [1]

3 annite + phlogopite = pyrope + muscovite + grossular [2]

Reaction [1] is temperature sensitive and reaction [2] is pressure sensitive. The multi-equilibrium program of Berman (1991) was used to calculate pressure and temperature for two domains in each rock. Results of the calculations are summarized in Figure 28. Although the results are somewhat scattered, calculated pressure varies between 1.5 and 3 kilobars and calculated temperature varies between 500 and 560°C. These results are in good agreement with the regional distribution of aluminosilicate polymorphs and staurolite.

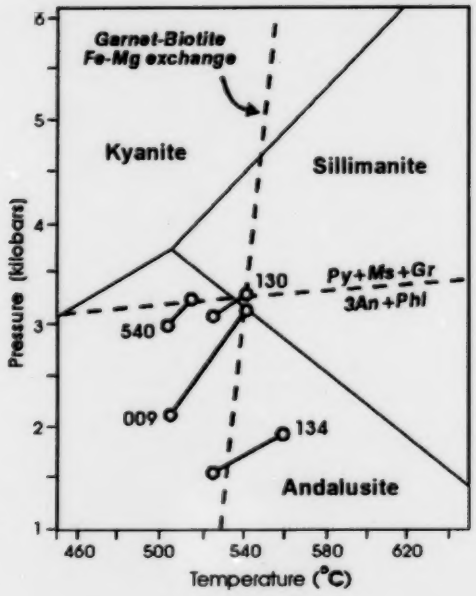

Figure 28. Pressure–temperature estimates for 4 rocks from the McKim Formation. See Figure 17 for locations of samples. Pressure estimates vary between 1.5 and 3 kilobars and temperature estimates vary between 500 and 560°C.

In summary, high-temperature, low-pressure metamorphism was roughly synchronous with development of the early mica foliation, which is commonly oriented at a low angle to bedding. In some areas, porphyroblast growth outlasted matrix recrystallization. Subsequent to high temperature – low pressure metamorphism, variably retrogressed porphyroblasts were rotated and both retrograde chlorite after garnet and matrix mica were crenulated. Since the crenulation cleavage is axial planar to large map-scale folds, it is inferred that such folds postdate peak metamorphism. The metamorphic zones are interpreted to have formed subparallel to bedding, gabbro bodies, and the penetrative mica foliation and then to have been folded during the crenulation cleavage-related folding.

Summary and Discussion

Regional maps of fold axial traces and faults in the Huronian Supergroup portray a beguilingly simple concave to the north structural grain (Figure 2). At a regional scale, one might consider the Quirke Lake syncline and the Sudbury Basin (syncline), and the Chiblow anticline and Baldwin anticline, to be related structures with variably plunging axes (Figure 2). However, interpretation of this pattern is complicated by several factors. First, the regional variations in structural style across the Murray fault make correlation difficult. For example, map-scale folds in the Aberdeen area are associated with an axial planar cleavage and could be interpreted as resulting from a single deformation. In May Township, regional folds are also associated with an axial planar cleavage, but these folds and related cleavage deform high-grade metamorphic rocks with earlier structural elements. Second, there are different time markers for the deformation in different areas (Figure 4). For example, north of the Murray fault, the only post-Huronian intrusions, other than relatively young diabase dikes (intruded circa 1.2 Ga), are the Nipissing gabbros (intruded circa 2.22 Ga). South of the Murray fault, there are granitoid intrusions (circa 1.75, e.g., Cutler Batholith). Third, the concave structural grain itself complicates correlation and elucidation of the timing of structural events. For example, it is unclear if there are two distinct fold sets (west-northwest striking west of the Cutler Batholith and east to east-northeast striking east of the Batholith), or, if an abrupt but progressive change in strike occurs in the Cutler area (Figure 2). Relationships between the two fold sets and related faults is further exacerbated by the presence of early high-grade deformation and metamorphism recorded in rocks south of the Murray fault, but not to the north and by Grenville orogenic influences near Sudbury. Several questions arise as a result of the complications mentioned above.

1) What constraints can be placed on the timing of regional deformational events?

2) Can large map-scale folds be correlated both along strike (e.g., Quirke Lake syncline and Sudbury Basin) and across the Murray fault (e.g., is the Chiblow anticline coeval with map-scale folds in May Township and further south)?

3) What is the origin of the high-grade metamorphism and the related structures?

4) What tectonic events (e.g. Penokean orogeny) likely resulted in the current structural and metamorphic pattern?

Evidence bearing on these questions is assembled below and observations required for their resolution are identified. West-northwest-striking dextral faults deserve special mention as they are associated with mineralization.

NW- TO WNW-STRIKING FAULTS AND MINERALIZATION

In previous sections, it was noted that northwest- to west-northwest-striking dextral faults cut earlier formed structures (e.g., Figures 17, 29). Evidence from existing maps combined with observations from this study indicate that, as a suite of structural elements, these faults may represent long-lived and multiply reactivated basement structures and, consequently, may represent interesting exploration targets.

In May Township, dextral faults offset the Murray fault zone and displace lower Huronian strata (Robertson and Siemiatkowska 1971). As the Murray fault is interpreted to have a significant component of post-peak metamorphic displacement, then these faults must be, in part, younger than both the regional metamorphism and the Murray fault. In May Township, the faults are associated with intense

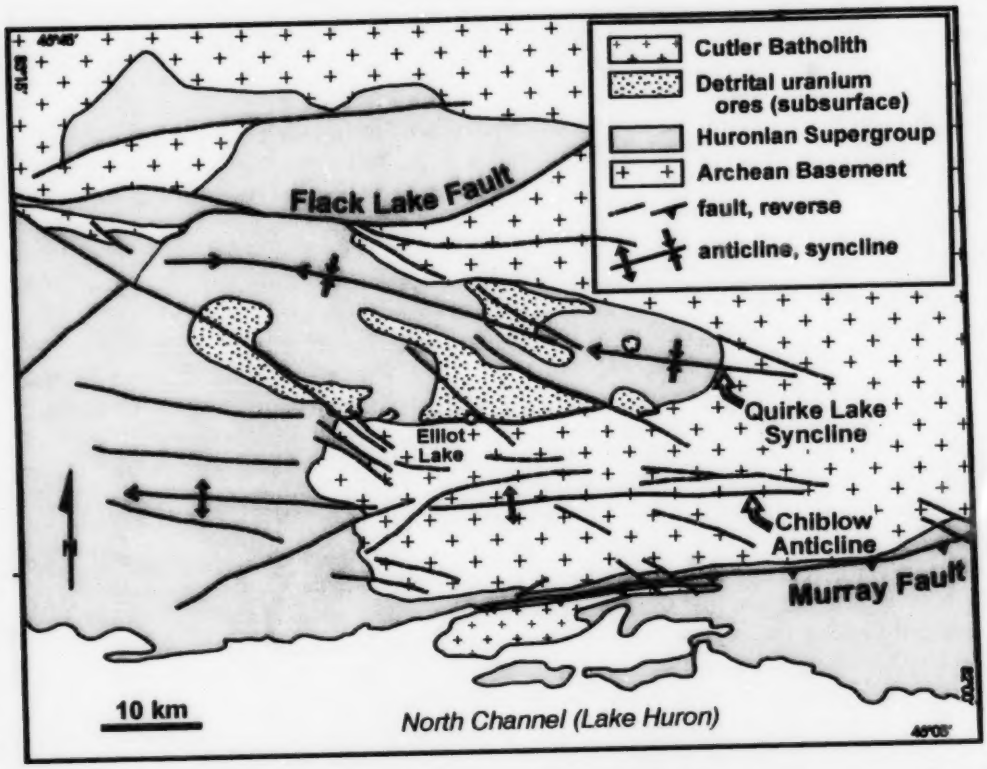

Figure 29. Location of detrital uranium ores of Elliot Lake mining camp with respect to northwest- to west-northwest-striking faults. See text for discussion and references.

Photo 8. East-northeast-striking silicified shear zone associated with copper mineralization. Photo from May Township.

silicification (Robertson and Siemiatkowska 1971) and shear-zone hosted copper mineralization. Some east- and east-northeast-striking faults are also silicified (Photo 8) and associated with copper mineralization in May Township. Since the silicified faults displace the Murray fault, or are parallel to the Murray fault, the emplacement of silica and related mineralization was introduced synchronously with, or subsequent to, displacement on the Murray fault.

In Proctor Township, Robertson (1977) reported a large northeast-striking "quartz vein". A diabase dike occupies the same structure, and Robertson (1977) reported chloritic zones in the quartz vein that he attributed to altered diabase. Consequently, the structure existed syn- to pre-2.22 Ga and then was permeated by silica-rich fluids post-2.22 Ga, consistent with the late displacement and silicification observed in May Township.

In the Quirke Lake syncline, the uranium ore horizons exhibit a strong west-northwest to northwest strike (Figure 29) that is commonly attributed to paleotopographic control during deposition that was defined by Archean lithostructural trends (e.g., Roscoe 1969; Derry 1960; Robertson (D.S.) and Steenland 1960). Alternatively, topographic control might be due to Proterozoic reactivation of Archean structures. Regional faults of the same orientation displace Huronian units and the Huronian–Archean boundary, implying reactivation of Archean basement structures at least post-deposition of Huronian strata.

Although it is difficult to constrain the entire history of any individual northwest- to west-northwest-striking fault, and not every fault is inferred to have the same history, the above relationships suggest that, as a suite of structural elements, these faults were repeatedly reactivated. They originated in Neoarchean time (2.7 to 2.6 Ga) in basement to the Huronian Supergroup. Basement topography was controlled by structures of this orientation prior to, and possibly during Huronian Supergroup deposition at 2.45 to 2.22 Ga. Nipissing gabbro utilized these structures at 2.22 Ga. Silica-rich fluids were focussed along the faults subsequent to the Nipissing intrusion at 2.22 Ga, and possibly subsequent to the latest displacement on the Murray fault, which itself was active until at least 1.75 Ga (see below). In short, these faults were episodically active through one billion years of Earth history. Given their association with hydrothermal activity, copper mineralization and the uranium ores of the Elliot Lake area, they should be a key prospecting target for syn-sedimentary, diagenetic, or fault-controlled hydrothermal mineral deposits.

TIMING AND CORRELATION OF DEFORMATION

The variation in structural style and constraints on timing of deformation in regions north and south of the Murray Fault require that the two regions initially be considered separately.

North of the Murray Fault

North of the Murray fault, rocks of low metamorphic grade are folded and reverse faulted about west-northwest-striking upright folds and north-northeast-verging reverse or thrust faults (Card et al. 1972; Zolnai et al. 1984). In the Aberdeen and Ten Mile Lake areas, the folds are commonly associated with weakly to moderately developed, steeply dipping, axial planar cleavage. Many of the Nipissing gabbro intrusions appear to be folded and truncated by faults whose surface traces are parallel to the axial traces of regional folds. In the Sudbury region, the Sudbury Igneous Complex (1.85 Ga) is folded and also has axial planar cleavage (e.g., Cowan and Schwerdtner 1994). On the basis of these observations, it would be inviting to assign a post-1.85 Ga age to the regional folding north of the Murray fault. It is also enticing to assume a single regional deformation given the relative structural simplicity of this area. Such an interpretation warrants examination, however, since some evidence exists for pre-2.22 Ga deformation.

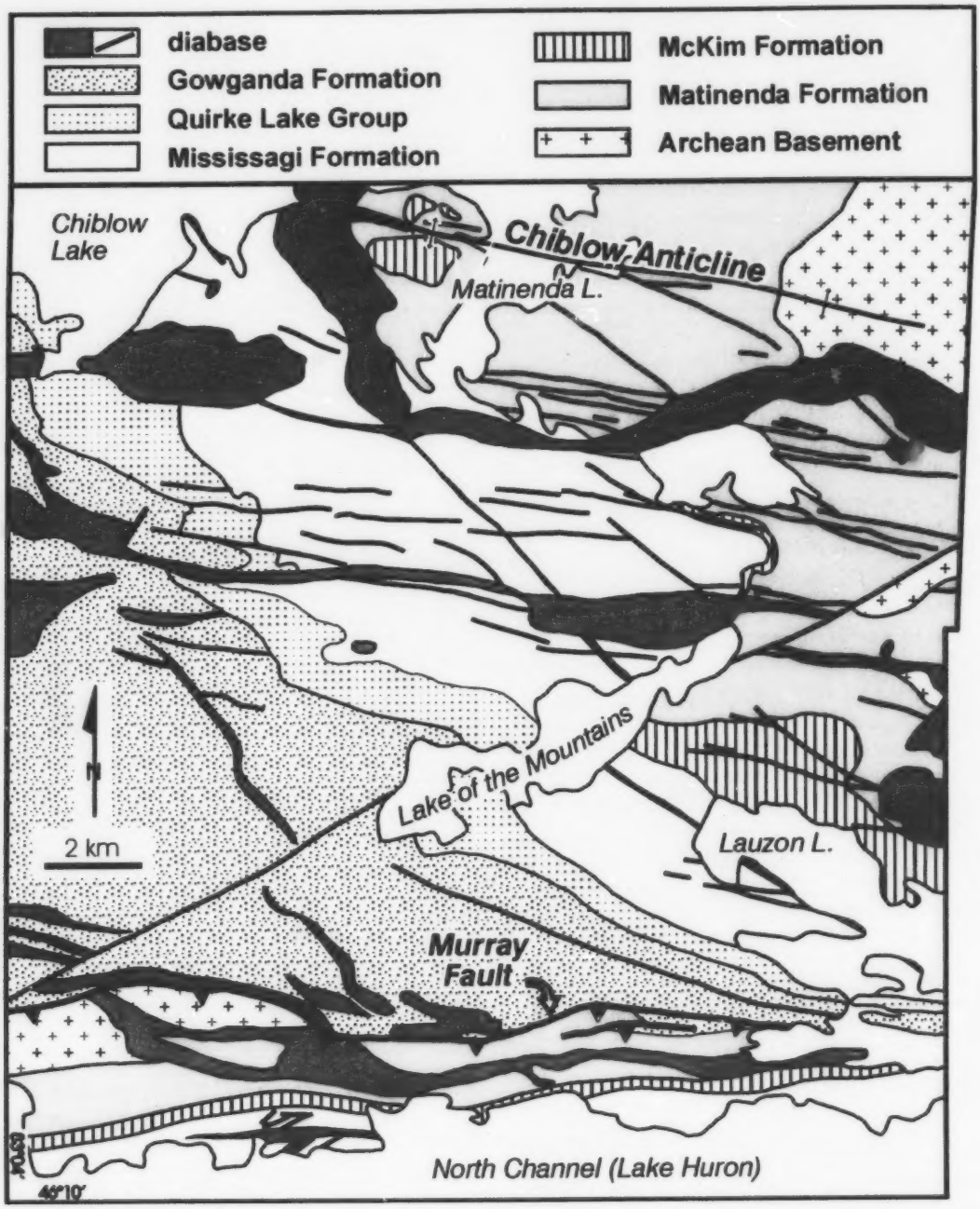

Figure 30. Geology of the south limb of the Chiblow Anticline (*from* Robertson 1964). Note that Nipissing gabbro sills (large bodies of "diabase") cross cut stratigraphy parallel to the axial plane direction of the Chiblow Anticline. Also note the thinner dikes that are emplaced parallel to the axial trace of the Chiblow Anticline, suggesting that axial planar fractures controlled their emplacement.

Robertson (1964) observed that there is a marked tendency for gabbro, or diabase, dikes to occupy structures parallel to the axial trace of the Chiblow anticline (Figure 30). Township maps from the area covering the Chiblow anticline and Quirke Lake syncline also exhibit this relationship. The maps also

indicate that gabbro bodies subparallel to strata in hinge regions are much thicker than the gabbro dikes in the orientation of the axial surface trace. Furthermore, Robertson's (1970) maps of Long and Spragge townships indicate that some imbrication of Huronian strata occurred prior to emplacement of the Nipissing gabbro. Specifically, between Wagush Lake and Long Lake, there is a sliver of Mississagi Formation sedimentary rocks along the north side of a large gabbro body (Figure 16). The Mississagi units strike easterly and both dip and face southward toward Archean basement from which it is separated by the gabbro. South of the gabbro, the Mississagi Formation – basement contact (without intervening gabbro) is again encountered and again Mississagi units dip and face south. Following the gabbro body westward to Hastie Lake, there is an apparent right-lateral offset of the Mississagi Formation – basement contact of more than 1 km. The offset and repetition of the south-facing basement–cover interface likely resulted from northerly directed reverse or reverse-oblique faulting. Apparently, the gabbro was emplaced along this fault surface. Since both the axial planar dikes and large gabbro bodies have been mapped as Nipissing, it would seem that some deformation of Huronian strata predated 2.22 Ga in the area north of the Murray fault between Sault Ste. Marie and Elliot Lake. This contrasts with both the folding in the Sudbury area, which is post 1.85 Ga, and some folding south of the Murray fault that postdates 1.75 Ga (*see below*). Therefore, alternate explanations of the apparent pre-2.22 Ga folding should be entertained. Three scenarios are discussed below (*see also* Figure 30); note that the scenarios are not mutually exclusive.

I) A SINGLE SYN- TO POST-NIPISSING DEFORMATION EVENT

The gabbro dikes and sills could have been emplaced during or subsequent to deformation along structurally prepared sites (e.g., scenario 1, Figure 31). For example, gabbro may have been emplaced along axial planar faults and dilatant zones in fold hinges. This scenario requires one deformational event north of the Murray Fault in the Sault Ste. Marie – Elliot Lake area circa 2.22 Ga, but also requires a much younger deformational event syn- to-post-1.85 Ga in the Sudbury area.

II) PRE- AND POST-NIPISSING DEFORMATION EVENTS

a) Early compressional deformation is pre- to syn-emplacement of gabbro dikes and sills (similar to that in "I" above) followed by later reactivation of faults and tightening of folds (*see* scenario 2, Figure 31). This scenario would allow the main regional folding, cleavage, and faulting events to be post-Nipissing; a scenario which would be compatible with post-1.85 Ga folding at Sudbury and post-1.75 Ga folding near Cutler (*see below*).

b) Early crustal flexure, not related to compressional deformation, resulting in fracturing and faulting of the basement and cover occurred prior to, or synchronous with, emplacement of gabbro dikes and sills. Locally, the faults were reverse-slip structures. Pertinent to this hypothesis is the observation by Roscoe (1969, p. 22) that the stratigraphic thickness of some formations decrease over the hinge area of the Chiblow anticline, suggesting that the area was a structural high or arch during deposition. Compressional deformation would follow gabbro emplacement resulting in regional folds (e.g., Quirke Lake and Chiblow folds) and faults, which, in this scenario, would be parallel to the axis of the earlier formed flexure. Like scenario "IIa", this scenario would allow the main regional folding, cleavage, and faulting events to be post-Nipissing.

III) TWO DIFFERENT EPISODES OF MAFIC INTRUSION

A third possibility, which is favoured in this report, is that there are two mafic intrusive events. One event would be represented by large Nipissing gabbro sills emplaced at 2.22 Ga subparallel to strata prior to the main regional folding. The second event would be represented by narrower mafic dikes that were emplaced along axial planar faults and fractures after folding (*see* scenario 3, Figure 31). In this scenario, the main regional folding would postdate 2.22 Ga, but predate the axial-planar mafic dikes. The reverse fault between Wagush and Long lakes would still be pre-Nipissing in age and would require some pre-Nipissing deformation.

Several observations could eliminate some of the above alternatives. First, structural mapping could determine whether the large strata-parallel gabbro bodies in fold hinges are folded or, alternatively, if they were emplaced subsequent to folding with their geometry controlled by previously folded strata. Relationships between fabrics and contact-metamorphic effects in fold hinges, as well as structural elements in the gabbro bodies, would be of prime concern. Crosscutting relationships between thicker strata-parallel gabbro bodies and the thinner axial-planar mafic dikes are required as are absolute age determinations on the axial-planar dikes.

The above discussion also holds implications for the relationship between the basement and the Huronian Supergroup cover. As stated earlier, a post-2.22 Ga detachment seems unlikely. However, given the presence of pre-Nipissing imbricate faults and the possibility of regional pre-Nipissing folding, a pre-Nipissing detachment remains possible. Mapping around the Quirke Lake syncline and the Chiblow anticline of both basement and cover near the basement-cover interface is required to address this issue.

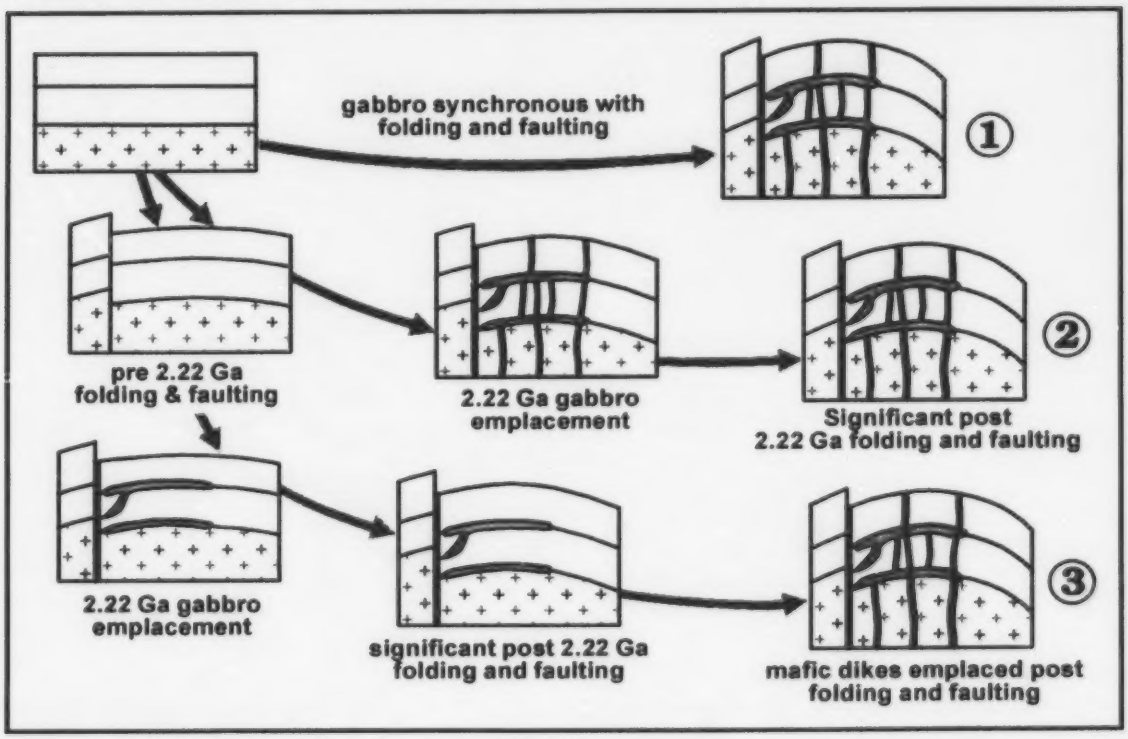
gabbro synchronous with folding and faulting
①
pre 2.22 Ga folding & faulting
2.22 Ga gabbro emplacement
Significant post 2.22 Ga folding and faulting
②
2.22 Ga gabbro emplacement
significant post 2.22 Ga folding and faulting
mafic dikes emplaced post folding and faulting
③

Figure 31. Alternative scenarios explaining gabbro and structure relationships in the region north of the Murray Fault. See text for discussion.

South of the Murray Fault

South of the Murray fault, there is good evidence for at least 3 significant deformational events. In the Whitefish Falls area, Young and Nesbitt (1985) present evidence for pre-Nipissing faulting and large-scale folding related to syn-depositional and/or post-depositional unconsolidated deformation of strata. In May Township, such structures were not recognized, however, two significant deformations that postdate Nipissing gabbro intrusions are recognized. For convenience, they will be called D_1 and D_2.

D_1 structures include the "early" penetrative mica foliation in metasedimentary and metagabbro units, related meso-scale to outcrop-scale isoclinal and rootless folds, and boudinaged bedding, veins, and gabbro. Metamorphic porphyroblasts south of the Murray fault grew syn- to post-development of the penetrative mica foliation. High extensional strain appears to be associated with this foliation. D_1 structures are deformed by regional D_2, west-northwest- and east-northeast-striking folds and faults that are associated with a well-developed, moderate to steeply dipping, crenulation cleavage. Textural evidence in May Township indicates that the D_2 cleavage postdates both crystallization of peak metamorphic assemblages and some retrogression of the porphyroblasts. Metamorphic zones are also interpreted to be folded during D_2. Regional folds, the Murray fault and other subparallel faults, are typical of structures commonly portrayed on regional maps and are interpreted here as significantly postdating peak metamorphism and related D_1 deformation. Noteworthy in this context is the observation from south of the areas examined in this study that "bedding plane foliation (is) cut by superimposed cleavage" that is axial planar to the McGregor Bay anticline (Card 1978a, p.189). Thus, the D_1–D_2 relationships may hold over the entire region south of the Murray fault.

The regional D_1 and D_2 structures south of the Murray fault clearly affect Nipissing gabbro and so must be younger than 2.22 Ga. Timing of D_2 may be further constrained by relationships involving deformation features observed in rocks of the Cutler Batholith.

DEFORMATION OF THE CUTLER BATHOLITH

The age of the Cutler Batholith was determined by Davidson et al. (1992) at circa 1.75 Ga. The relationship of this intrusion to structural features in Huronian Supergroup rocks, therefore, is useful in establishing the timing of deformation events. Cannon (1970) and Robertson (1970) noted the presence of a tectonic fabric in the Cutler Batholith. Cannon (1970) concluded that the batholith was emplaced synchronously with folding because foliation in the batholith is approximately parallel to the axial surface trace of folded Huronian–Nipissing units. A brief 2-day examination of structural relationships near Cutler combined with the structural analysis of May Township confirms Cannon's interpretation and furthermore, as outlined below, indicates the emplacement of the Cutler Batholith is likely synchronous with D_2 deformation.

Mapping by Robertson (1970, 1977) and Cannon (1970) indicates the presence of several antiforms and synforms striking subparallel to the trace of the Murray fault (Figure 32). The folds are delineated by metagabbro (Nipissing), bedding, and by granitic pegmatite bodies related to the Cutler Batholith. Examination of the noses of some folds indicates that the McKim Formation and contained bedding-parallel metagabbro bodies have a strong near-bedding-parallel "D_1" mica (+ amphibole in the case of the metagabbro units) foliation that wraps around the noses of the folds. This is comparable to relationships established above for May Township. Examination of the fold noses also indicate that a well-developed "D_2" axial-planar crenulation cleavage is present and is parallel to variably developed quartz-mica foliation in the granitic pegmatite bodies and to foliation reported from the main mass of the Cutler Batholith (*see* foliation in batholith indicated on maps *in* Robertson 1970, 1977). In this regard, it should

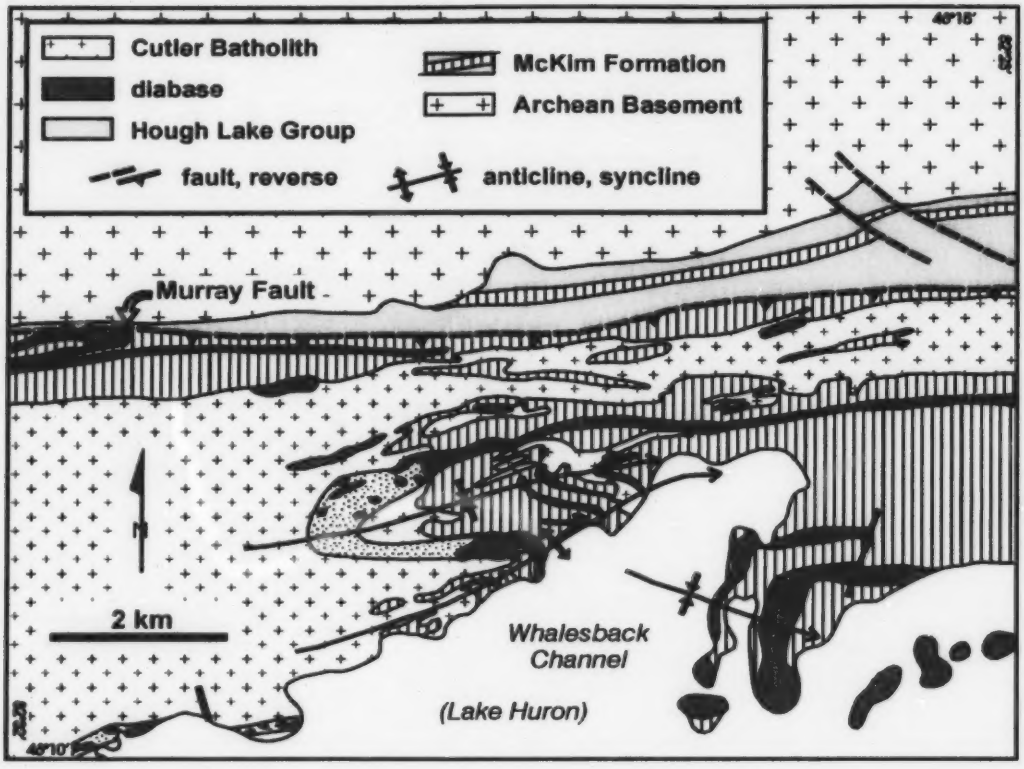

Figure 32. Geology of the Cutler batholith area (*from* Robertson 1977).

be noted that it is critical that fold noses, and not limbs, be examined since on the fold limbs the D_2 cleavage and D_1 mica foliation are subparallel and difficult to distinguish. This is apparently also true for regions proximal to the Murray fault where D_2 cleavage is commonly well developed. Furthermore, although many granitic pegmatite bodies are folded (Photo 10), many are subparallel to the axial planes of the folds and the D_2 cleavage (Photo 9). Photos 9 and 11 show dikes crosscutting the D_1 foliation at a high angle with no evidence of related deformation, such as cleavage within the dikes or folding of the dike margins. Other dikes occupy small-displacement fault planes that are parallel to the crenulation cleavage and cut across D_1 fabric at a high angle (Figure 33). Collectively, these observations indicate that

1) the McKim Formation and Nipissing gabbro record D_1 deformation fabrics that are not recorded by the Cutler Batholith and related granitic pegmatite bodies;

2) as Cannon (1970) concluded, the batholith and related rocks were emplaced during a regional folding event;

3) the folding event identified by Cannon (1970) is the regional "D_2" event established above which must then have occurred circa 1.75 Ga (age of Cutler Batholith from Davidson et al. 1992);

4) D_1 and associated high-grade metamorphism in this area is pre 1.75 Ga, consistent with Card's (1978b) conclusion that high-grade metamorphism in the Sudbury area was pre 1.85 Ga.

The questions of timing and correlation of large-scale folds along strike and across the Murray fault require additional observations in order to be resolved. If the large-scale folds and faults are correlated on the basis of their subparallelism, then available age constraints would place this folding circa 1.75 Ga; certainly it would postdate 1.85 Ga Sudbury Igneous Complex.

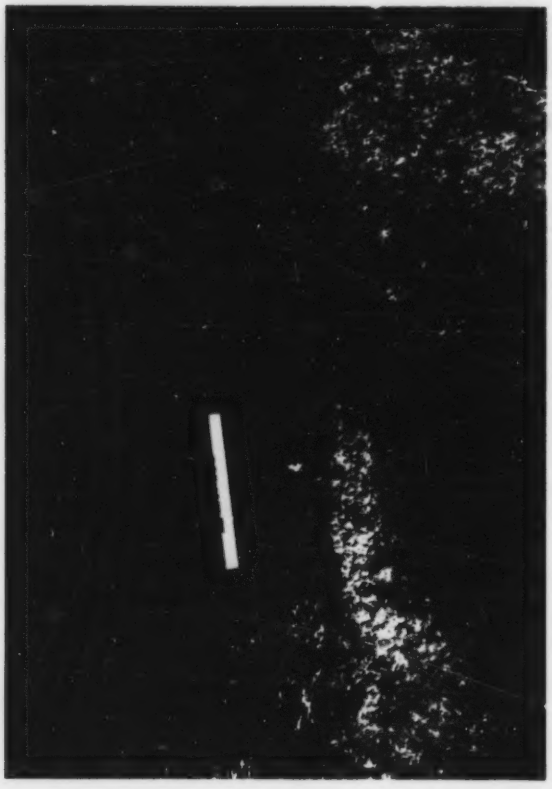

Photo 9. Granitic dike related to Cutler batholith that intruded subparallel to axial plane of folded bedding and penetrative mica foliation in McKim Formation metapelite. Dike and axial plane of crenulation cleavage are subparallel. Photo from west of Spanish near Lake Huron.

Photo 10. Pegmatitic material related to Cutler batholith that is folded and foliated by D_2 deformation. Photo from west of Spanish near Highway 17.

Photo 11. Granitic dikes of Cutler batholith, which postdate early bedding-parallel mica foliation, but are crudely aligned parallel to later, crenulation–cleavage-related folds. Photo from west of Spanish near Lake Huron.

Figure 33. Sketch map illustrating emplacement of granitic dikes of Cutler batholith along D_2 axial plane directions. At this outcrop, penetrative foliation is parallel to bedding and crenulated and folded by D_2 axial planar cleavage and folds. The granitic dikes in this area, then, postdate the early penetrative foliation.

ORIGIN OF MEDIUM-GRADE METAMORPHISM

The origin of high-grade metamorphic assemblages involving staurolite and biotite in the McKim Formation in the hanging wall of the Murray fault is one of the most enigmatic aspects of the tectonic history of the Southern Province. Most authors (e.g., Card 1978; Zolnai et al. 1984; Jackson 1994b) have related the high-grade metamorphism to compressional orogeny generally inferred to be the Penokean orogeny circa 1.85 to 1.82 Ga. Zolnai et al. (1984) and Jackson (1994b) attributed the metamorphism to crustal thickening, whilst Card (1978b) appealed to "heat pipes" of rapid and focussed heat flow. Jackson (1994b), following Holst (1984), suggested that imbrication of nappes early in the compressional history of the orogen could induce subhorizontal flow and increase thermal gradients, thereby explaining both the pervasive penetrative foliation at a low angle to bedding and the high-grade metamorphism (e.g., Figure 34a-i'). This explanation of the metamorphism encounters several difficulties. First, the lack of regional fold-closures to the postulated nappes would require that either the nappes are thrust sheets or they are nappes with attenuated poorly developed overturned limbs (e.g., Figure 34a-i). Second, at a regional scale, it is not clear that there is any evidence for thick thrust sheets having been displaced for significant horizontal distances. Third, the geobarometry indicates relatively low-pressure (2 to 3 kilobars) metamorphism at high-temperatures in contrast with the 6 to 7 kilobar pressure estimates for Penokean metamorphism in Minnesota by Holm and Selverstone (1990). In fact, the estimated paleopressures of 2 to 3 kilobars translates to 6 to 10 km of overburden at the time of metamorphism. This thickness is generally at or below the estimated thickness of the stratigraphic column south of the Murray fault (e.g., Bennett et al. 1991). In other words, the high-temperature metamorphism occurred at or below pressure corresponding to the thickness of the Huronian clastic prism and would seem to preclude crustal thickening as the origin of the metamorphism.

An alternate explanation is that the medium-grade metamorphic assemblages developed as a result of crustal extension (e.g., Figure 34a-i) and increased mantle heat flow. Extension could explain the presence of pervasive low-angle foliation and related high-strain elements and the absence of convincing regional thrust panels. High heat flow is commonly associated with crustal extension and related mantle upwelling and could account for the relatively high temperatures obtained at relatively low pressures (e.g., Wickham and Oxburgh 1985, 1987). An extensional model could also provide an explanation for the somewhat enigmatic Nipissing gabbro event at 2.22 Ga. Although the Nipissing gabbros are metamorphosed and reflect a similar metamorphic pattern (Card 1978b; Blonde 1996) and structural history as the McKim Formation metasedimentary rocks, they may, nevertheless, represent a pre-metamorphic magmatic expression of the postulated extension and mantle upwelling. Crustal extension and mantle upwelling at approximately 2.22 Ga could have resulted in emplacement of Nipissing gabbros into the overlying Huronian Supergroup cover. Alternatively, there may have been several "mantle disturbances", one that generated Nipissing magmatism, and a later one that generated crustal extension, related deformation and metamorphism. In either scenario, both the gabbros and the cover rocks would have subsequently been metamorphosed as the thermal anomaly associated with extension and mantle upwelling migrated upward. Potentially, heat flow and strain were highly focussed in the deeper formations south of the Murray fault above a basal extensional detachment.

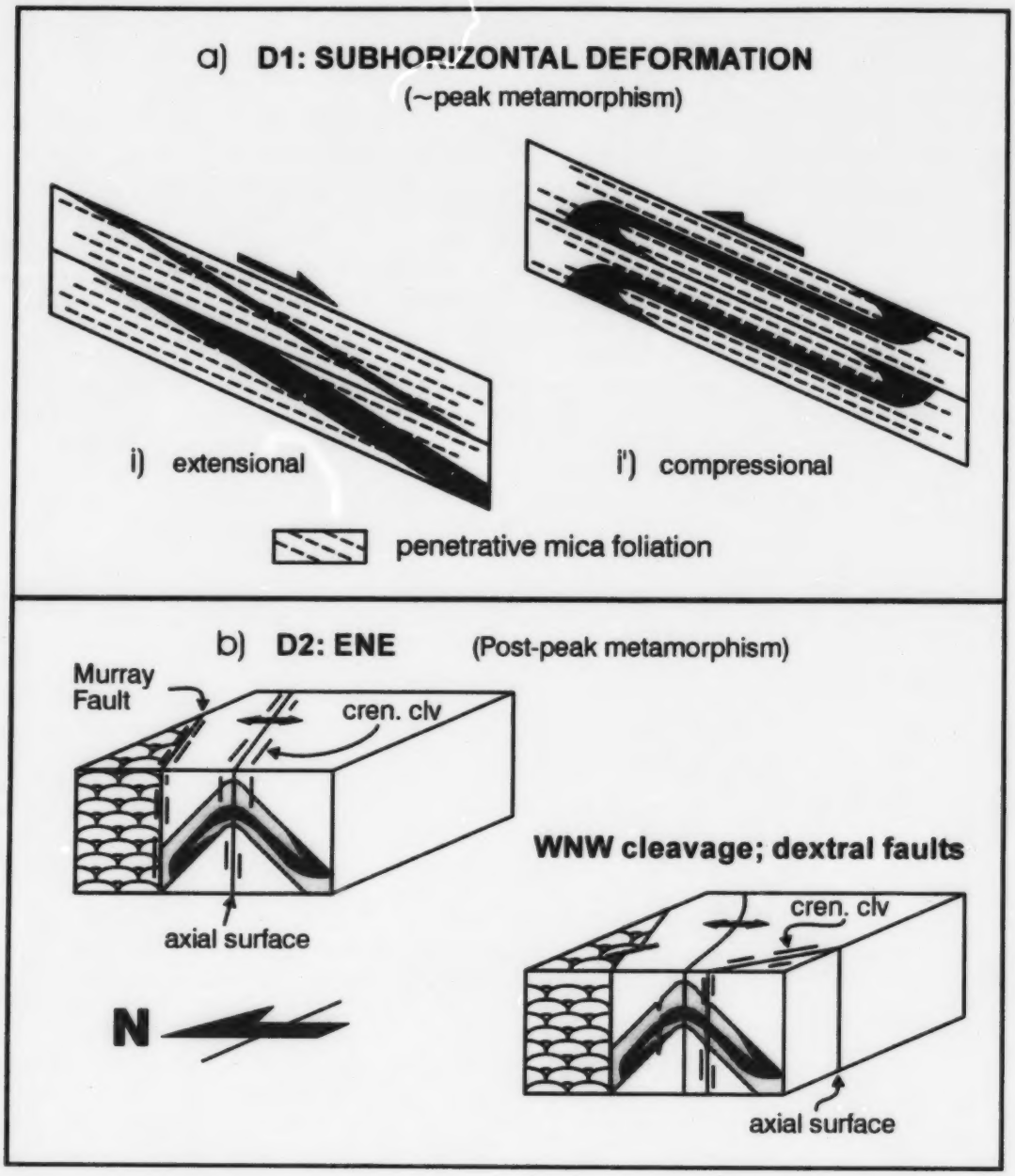

Figure 34. a) Alternate scenarios explaining origin of low-angle foliation and peak metamorphism. i) Foliation forms during extensional deformation and related thermal anomaly. i') Foliation forms during thrusting and resultant heating. The lack of documented overthrusting and the low pressure of regional metamorphism supports scenario (i). b) Schematic illustration of post-metamorphic regional folds and faults.

COMMENT ON SOUTHERN PROVINCE TECTONICS

It is generally accepted that the Huronian Supergroup was deposited during rift-related extension and subsequent thermal subsidence of Archean continental crust. Regional folds and faults, and high-grade metamorphism south of the Murray fault are generally attributed to the compressional Penokean orogeny at 1.85 to 1.82 Ga, despite the recognition of earlier and later deformations. As indicated above, the structural and metamorphic data are, however, permissive of other interpretations. In the hope of stimulating the collection of data that will further elucidate the tectonic evolution of the Southern Province, a variation on the above tectonic scenario is suggested below. Constraints on the events discussed below are summarized in Figure 35. It was proposed in the discussion above that high-grade metamorphism, early deformation and Nipissing gabbro emplacement may all be related to extensional tectonism. If so, then what is their tectonic origin?

In general, rifting of the Archean craton and deposition of the Huronian Supergroup is thought to have occurred between 2.45 Ga and 2.22 Ga. Within this 230 million year interval, there are presently no constraints on when most Huronian strata were deposited. In this context, it may be significant that an angular unconformity is present between the volcanic rocks (2.45 Ga) and the overlying Hough Lake Group. In addition, no volcanic units (e.g., thin flows or ash beds) have been reported from within strata overlying the volcanic formations (although minor wacke is present within some of the volcanic belts). Potentially, then, the Hough Lake, Quirke Lake and Cobalt groups might have been deposited tens or even hundreds of millions of years following volcanism; perhaps coinciding closer in time with Nipissing magmatism than is commonly accepted. Examination of gabbro–sediment relationships, particularly in upper Huronian Supergroup strata, might clarify whether or not Nipissing gabbro was emplaced into unconsolidated or partially lithified sediment.

Noting the exceptional correlation of strata between the Huronian Supergroup and the Snowy Pass Supergroup in Wyoming *on the other side of the Trans-Hudson Orogen,* Roscoe and Card (1993) suggested that the Superior and Wyoming cratons were once contiguous and, further, that Huronian Supergroup sedimentation *predates* the rift to drift transition. They postulated that the transition occurred post 2.2 Ga (age of Nipissing gabbro), perhaps circa 2.1 Ga (age of Biscotasing and related dike swarms). Roscoe and Card's (1993) model provides a potential framework for Nipissing magmatism, "early" high-temperature – low-pressure metamorphism and related subhorizontal deformation. Rifting, and eventual drifting, of the Superior and Wyoming cratons between 2.2 and 2.1 Ga may have subjected deep parts of the basin to elevated heat flow resulting in high-temperature – low-pressure metamorphism following Nipissing intrusion. In this scenario, the early high-strain deformation and medium-grade metamorphism (e.g., D_1 elements in May Township) would substantially predate the Penokean orogeny at 1.85 to 1.82 Ga. This is consistent with the observation of Card (1978b) that high-grade metamorphism predates the 1.85 Ga Sudbury Igneous Complex. A solution to the problem of significant pre-Nipissing deformation in rocks north of the Murray Fault would, however, be required were such deformation to be rigorously established to be of that age (*see* discussion in "Timing and Correlation of Deformation").

South of the Murray fault, emplacement of the Cutler Batholith at 1.75 Ga postdated early D_1 structures and, by inference, the associated high-grade metamorphism, and appears to be synchronous with development of D_2 map-scale folds and associated axial planar cleavage which deform D_1 elements. In addition, significant displacement occurred on the Murray Fault during D_2. This may imply that much of the large-scale folding and related fault displacement is circa 1.75 Ga and therefore followed Penokean orogenesis.

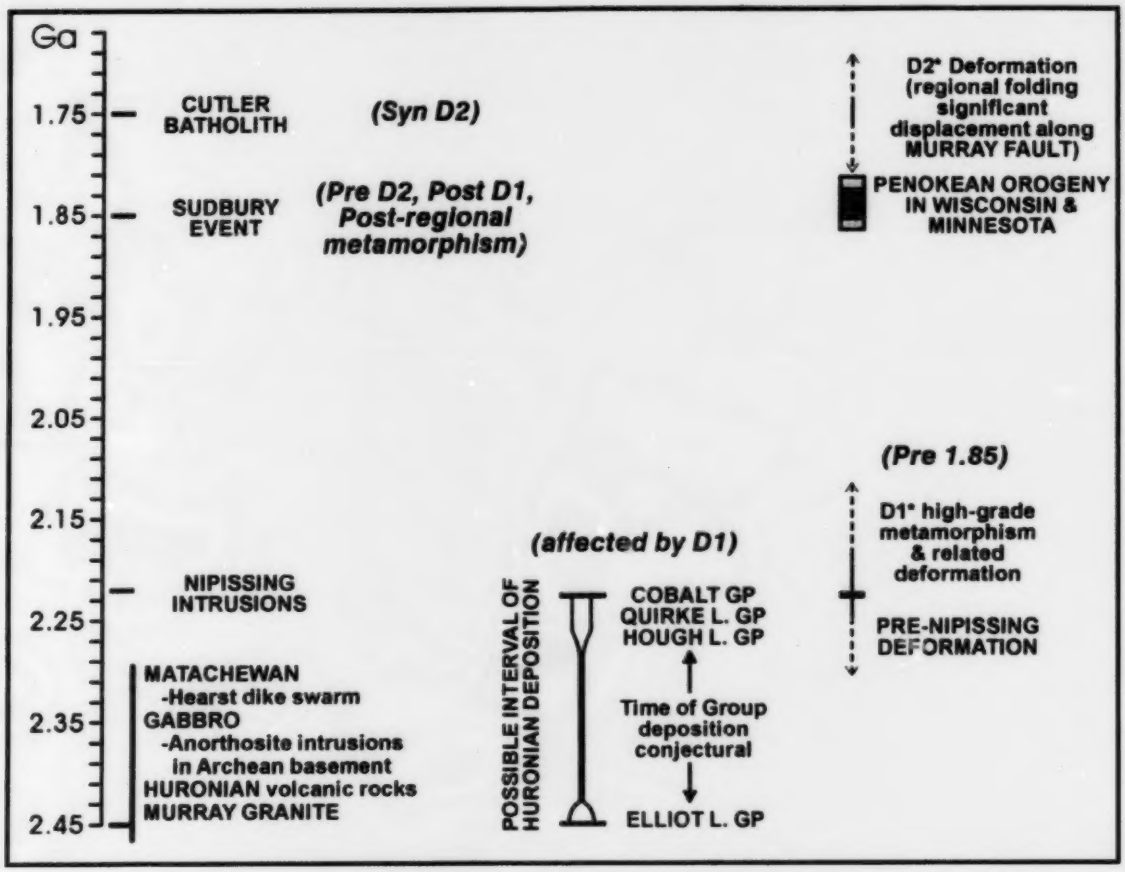

Figure 35. Time chart illustrating possible timing of regional events. Deposition of the Hough, Quirke, and Cobalt groups may have occurred substantially after initial volcanism at 2.45 Ga. Relatively high-grade metamorphism may shortly follow emplacement of the Nipissing gabbro at 2.22 Ga. Large-scale folding, attributed to D_2 deformation, may be roughly synchronous with emplacement of the Cutler batholith.

Davidson et al. (1992) questioned the existence of Penokean-related events in the Huronian primarily because of an absence of magmatic ages of that interval. As pointed out by Card (1992), the absence of such magmatic ages is inconclusive. However, the arguments laid out above suggest significant post-1.75 Ga deformation and allow for the possibility that early deformation "shortly" followed ~2.22 Ga, thereby supporting Davidson et al.'s (1992) notion. Davidson et al. (1992) noted that the Yavapai and Mazatzal orogenies in the mid-continent region of the United States have ages comparable to that of the Cutler Batholith. Potentially, D_2 folds south of the Murray fault could be related to one of these orogenic events rather than the Penokean orogeny. A structural expression of the Penokean orogeny then would have to be sought in the D_1 structures associated with high-grade metamorphism; although at present the author favours an extensional setting for the metamorphism and related structures. At present, the age of D_1 events are constrained only to post 2.22 Ga and pre 1.85 Ga. U/Pb ages from metamorphic titanite from metagabbro units would greatly clarify the timing of this significant low-pressure, high-temperature deformational event.

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Metric Conversion Table

Conversion from SI to Imperial			Conversion from Imperial to SI		
SI Unit	*Multiplied by*	*Gives*	*Imperial Unit*	*Multiplied by*	*Gives*
		LENGTH			
1 mm	0.039 37	inches	1 inch	**25.4**	mm
1 cm	0.393 70	inches	1 inch	**2.54**	cm
1 m	3.280 84	feet	1 foot	**0.304 8**	m
1 m	0.049 709	chains	1 chain	20.116 8	m
1 km	0.621 371	miles (statute)	1 mile (statute)	**1.609 344**	km
		AREA			
1 cm^2	0.155 0	square inches	1 square inch	**6.451 6**	cm^2
1 m^2	10.763 9	square feet	1 square foot	**0.092 903 04**	m^2
1 km^2	0.386 10	square miles	1 square mile	2.589 988	km^2
1 ha	2.471 054	acres	1 acre	0.404 685 6	ha
		VOLUME			
1 cm^3	0.061 023	cubic inches	1 cubic inch	**16.387 064**	cm^3
1 m^3	35.314 7	cubic feet	1 cubic foot	0.028 316 85	m^3
1 m^3	1.307 951	cubic yards	1 cubic yard	0.764 554 86	m^3
		CAPACITY			
1 L	1.759 755	pints	1 pint	0.568 261	L
1 L	0.879 877	quarts	1 quart	1.136 522	L
1 L	0.219 969	gallons	1 gallon	**4.546 090**	L
		MASS			
1 g	0.035 273 962	ounces (avdp)	1 ounce (avdp)	28.349 523	g
1 g	0.032 150 747	ounces (troy)	1 ounce (troy)	**31.103 476 8**	g
1 kg	2.204 622 6	pounds (avdp)	1 pound (avdp)	**0.453 592 37**	kg
1 kg	0.001 102 3	tons (short)	1 ton (short)	**907.184 74**	kg
1 t	1.102 311 3	tons (short)	1 ton (short)	**0.907 184 74**	t
1 kg	0.000 984 21	tons (long)	1 ton (long)	**1016.046 908 8**	kg
1 t	0.984 206 5	tons (long)	1 ton (long)	**1.016 046 90**	t
		CONCENTRATION			
1 g/t	0.029 166 6	ounce (troy)/ ton (short)	1 ounce (troy)/ ton (short)	34.285 714 2	g/t
1 g/t	0.583 333 33	pennyweights/ ton (short)	1 pennyweight/ ton (short)	1.714 285 7	g/t

OTHER USEFUL CONVERSION FACTORS

	Multiplied by	
1 ounce (troy) per ton (short)	31.103 477	grams per ton (short)
1 gram per ton (short)	0.032 151	ounces (troy) per ton (short)
1 ounce (troy) per ton (short)	20.0	pennyweights per ton (short)
1 pennyweight per ton (short)	0.05	ounces (troy) per ton (short)

Note: Conversion factors which are in bold type are exact. The conversion factors have been taken from or have been derived from factors given in the Metric Practice Guide for the Canadian Mining and Metallurgical Industries, published by the Mining Association of Canada in co-operation with the Coal Association of Canada.